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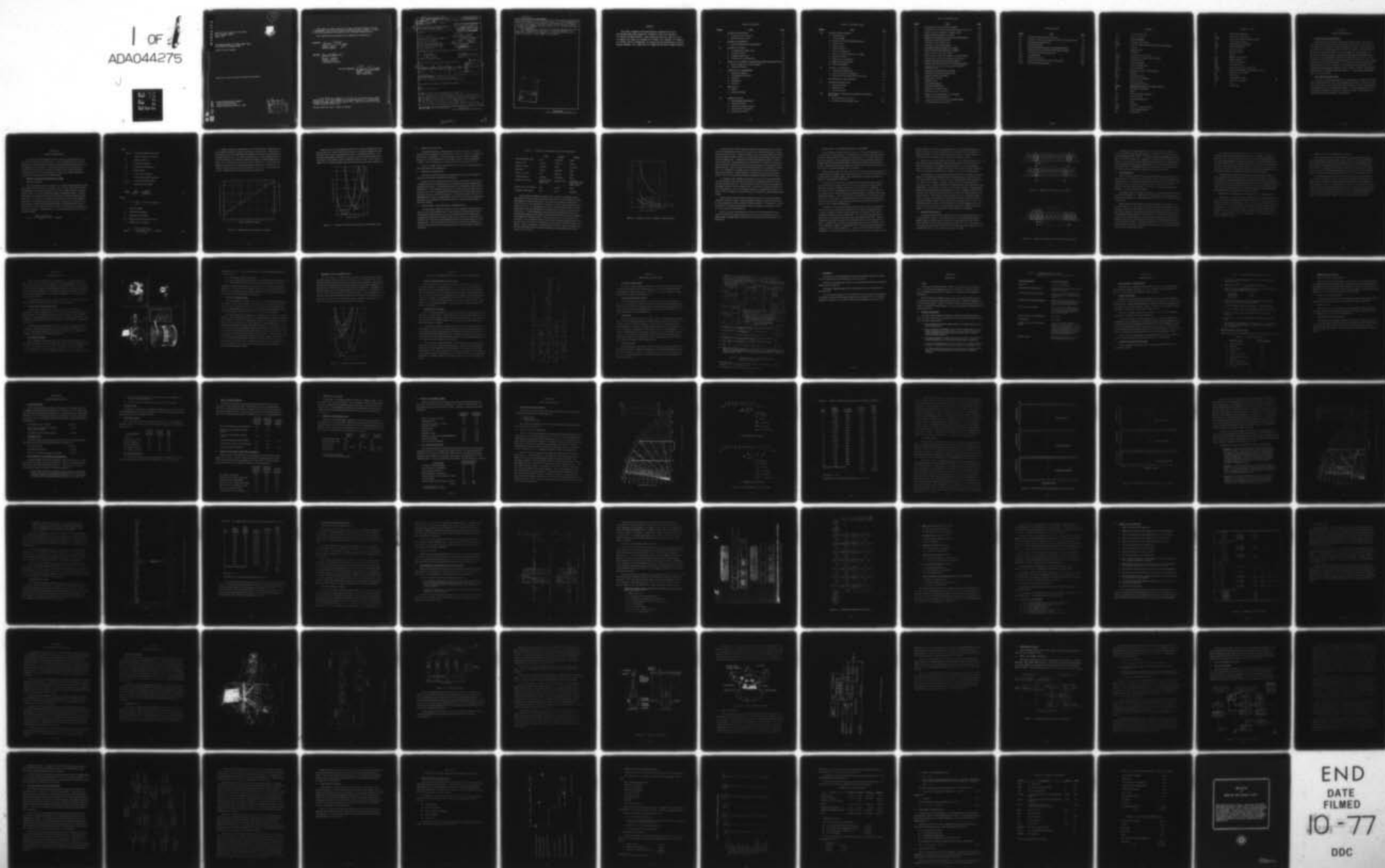

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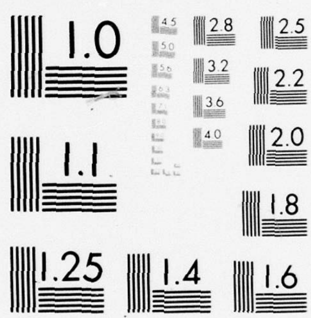

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RADC-TR-77-263, Volume III (of three)
Final Technical Report
August 1977

UNATTENDED/MINIMALLY ATTENDED RADAR STUDY
3-D (Minimally Attended) Radar

General Electric Company

Approved for public release; distribution unlimited.

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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The purpose of the Unattended/Minimally Attended Radar Study was to determine the exploratory and advanced development activities necessary to support the development of Unattended (2-D) and Minimally Attended (3-D) Radars. Volume III describes the radar concepts that were considered for the 3-D Minimally Attended role, and the selection of the recommended design.

The 3-D Radar provides accurate range, azimuth, and height data on every target in its surveillance volume, which extends to 150 nmi or 200 nmi (2-radar

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designs were generated for the two requirements). The principal design ground rules included high reliability and ease of maintenance (to be maintained by a minimum crew), automatic detection, automatic clutter adaptation, automatic performance monitoring/fault location (PM/FL) and use of low-risk technology at a reasonable investment.

The recommended system is an L-band, all solid-state phased array, pencil-beam radar. The radar can be maintained by a three-man maintenance crew. Radar control, PM/FL, clutter adaptation, and output data interface are all under the control of a (dual) general purpose computer.

PREFACE

This report, prepared by the General Electric Company for Rome Air Development Center under Contract No. F30602-76-C-0380 was compiled by T.B. Shields, the Study Director. Major contributors were S.E. Bell, M.I. Fox, L.D. Hayes, R.D. King, J.W. Krueger, D.J. Murrow, N.A. Schmitz, F.D. Shapiro, J.J. Stewart, and R.D. Wengenroth. B. Cameron was the General Electric Company Program Manager. R.A. Ackley and A.S. Briggs were the RADC Program Monitors.

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GLOSSARY

ACP	Azimuth Change Pulse
ACU	Array Control Unit
A/D	Analog-to-Digital
AGC	Automatic Gain Control
ASCII	American Standard Code for Information Interchange
Az	Azimuth
BT	Bandwidth Time
C	Centigrade
CFAR	Constant False Alarm Rate
CRPL	Central Radio Propagation Laboratory
CRT	Cathode Ray Tube
csc^2	Cosecant Squared
CSR	Clutter-to-Signal Ratio
ECM	Countermeasures
ECCM	Electronic Counter Countermeasures
El	Elevation
FIFO	First In-First Out
FFT	Fast Fourier Transform
GP	General Purpose
IF	Intermediate Frequency
IFFDC	Identification Friend or Foe Data Controller
IOC	Input/Output Controller
K	Kelvin
LFM	Linear Frequency Modulated
LO	Local Oscillator
LRU	Least Replaceable Unit
m	Meter
msin	Millisines
MTBF	Mean Time Between Failures
MTI	Moving Target Indicator
nmi	Nautical Mile

GLOSSARY (Cont)

P_D	Probability of Detection
P_{FA}	Probability of False Alarm
PMSD	Performance Monitoring Status Display
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
PWB	Printed Wire Board
RF	Radio Frequency
rms	Root-mean-square
s	Second
SCR	Signal-to-Clutter Ratio
SLB	Sidelobe Blanker
SNR	Signal-to-Noise Ratio
SOW	Statement of Work
SPDC	Signal Processor Data Controller
S/SPDC	Synchronizer/Signal Processor Data Controller
STC	Sensitivity Time Control
SR	Short Range
TWT's	Traveling Wave Tubes
UHF	Ultra High Frequency
W	Watt
μs	Microsecond

SECTION I

SYSTEM REQUIREMENTS

1. PERFORMANCE REQUIREMENTS

The performance parameters of the Statement of Work (SOW), for the type B (3-D) radar, stipulate that it will provide detection and track for up to 100 aircraft in a coverage volume extending to a range of either 200 or 150 nmi, an altitude of up to 100,000 and to an elevation angle of 25°, and 360° in azimuth. The output track data will contain Identification Friend or Foe (IFF), height, and positional data on a spectrum of aircraft ranging from small single engine planes with ground speeds as low as 80 kts, to large supersonic aircraft with velocities of up to 2400 kts. The probability of track initiation and maintenance shall be 95% for aircraft in the coverage volume, and 99.9% for dropping track. Track initiate and track drop will be accomplished within 48 s and 36 s, respectively. Detection and track capability will be maintained in clutter regions created by terrain, weather, or aurora. The radar will also be capable of detecting zero Doppler targets (i.e., those with tangential flight paths) over clutter regions.

2. EQUIPMENT REQUIREMENTS

The thrust in establishing the equipment configuration is to maximize reliability, while minimizing life cycle costs and maintenance requirements. The goal is to provide a system that may be operated with minimal attention, and with a growth potential for being operated in a totally unattended manner. To obtain these goals the design must optimize redundancy, modularity, simplicity of design, graceful degradation, built-in monitoring, fault analysis, and self repair.

SECTION II

SYSTEM OPTIMIZATION

As a first step in the design process flow, the system requirements were allocated to form subsystem requirements. A series of tradeoff studies were then undertaken to optimize the radar parameters using the constraints placed on the system design by the requirements. These radar parameters in turn were used to formulate candidate systems which were examined for their inherent reliability, maintainability, life cycle cost, simplicity of design, and available technology to establish a baseline design which was then finalized.

1. SYSTEM PERFORMANCE TRADEOFF STUDIES

a. POWER APERTURE

The "search range equation", Equation (2-1) equates average transmitter power times effective aperture area to a constant. This, of course, only holds true where the probability of detection, probability of false alarm, target radar cross section, scanned volume, frame time, and target range are established factors. Using this relationship, the power-aperture may be optimized as a function of detection range. In the case of a 3-D radar, this function is not applicable, as the vertical angular sensitivity for the height measurement must also be considered. The equation may be modified by substituting in the generalized form of the angular error equation, Equation (2-2). This yields Equation (2-3), where the power times aperture squared is equal to a constant. Using Equation (2-3), the power-aperture may be optimized for the 3-D radar.

$$P_{avg} A = \frac{(SNR)_n \, \Omega \, 8\pi \, R^4 \, K \, T_n \, L}{T_f \, \sigma} = \text{Constant} \qquad (2\text{-}1)$$

where

$(SNR)_n$ = Integrated signal-to-noise ratio

Ω = Scanned volume in steradians

R = Range in meters

K = Boltzmann's constant

T_n = System noise temperature

L = System losses

T_f = Frame time in seconds

σ = Target cross section in meters

P_{avg} = Average transmitter power

A = Aperture area in meter^2

$$(SNR)_n = \frac{\phi^2}{K_s^2 e^2} = \frac{1.28\, c^2}{K_s^2 f_t^2 e^2 A} \qquad (2\text{-}2)$$

where

$\phi = 1.13 \dfrac{c}{f_t \sqrt{A}}$ = Elevation beamwidth

c = Velocity of light

f_t = Transmitter frequency

A = Aperture area in meter^2

K_s = Angle system error-detection slope

e = Angular error in radians

$$P_{avg} A^2 = \frac{1.28\, c^2\, \Omega\, 8\pi R^4 K T_n L}{f_t^2 K_s^2 e^2 T_f \sigma} = \text{Constant} \qquad (2\text{-}3)$$

A further constraint on aperture size is the restriction on the beamwidth dictated by angular resolution, elevation measurement, and scan rates. The maximum aperture size or gain is established by the minimum beam size to scan the volume in the required frame time. The minimum aperture size is in turn constrained by the azimuth resolution, and maximum elevation beamwidth for accurate height measurement. These constraints are shown graphically in Figure 2-1. The area above the diagonal line represents the operating conditions prohibited by the dwell-time constraint, and sets the maximum allowable antenna gain at 41 dB. The minimum gain is 34 dB, established by the resolution/accuracy requirements.

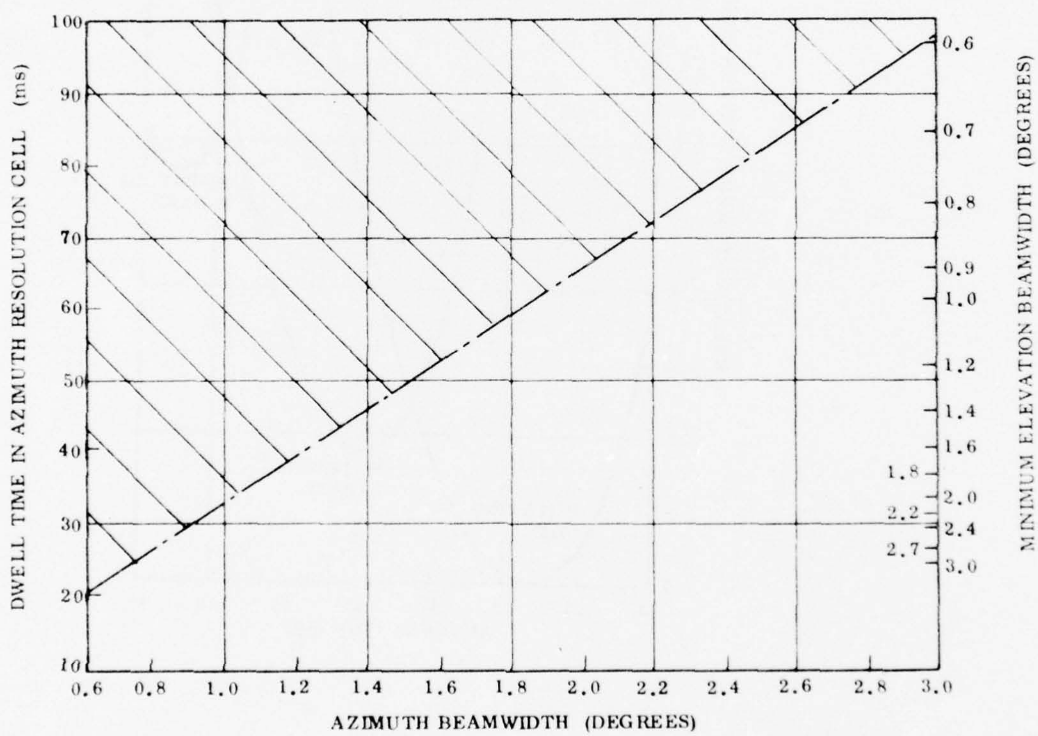

Figure 2-1. Scanning Pencil Beam Antenna Constraints

System cost may be determined by taking the cost of the transmitter in dollars per watt times the average output power; the cost of the antenna in dollars per meter squared times the area; a constant for the receiver, signal processor; etc. Combining this relationship with Equation (2-3) and taking the derivative equated to zero, the optimum power aperture may be established in terms of cost. This is shown in Figure 2-2 for a range of antenna gains with no constraint on maximum antenna size.

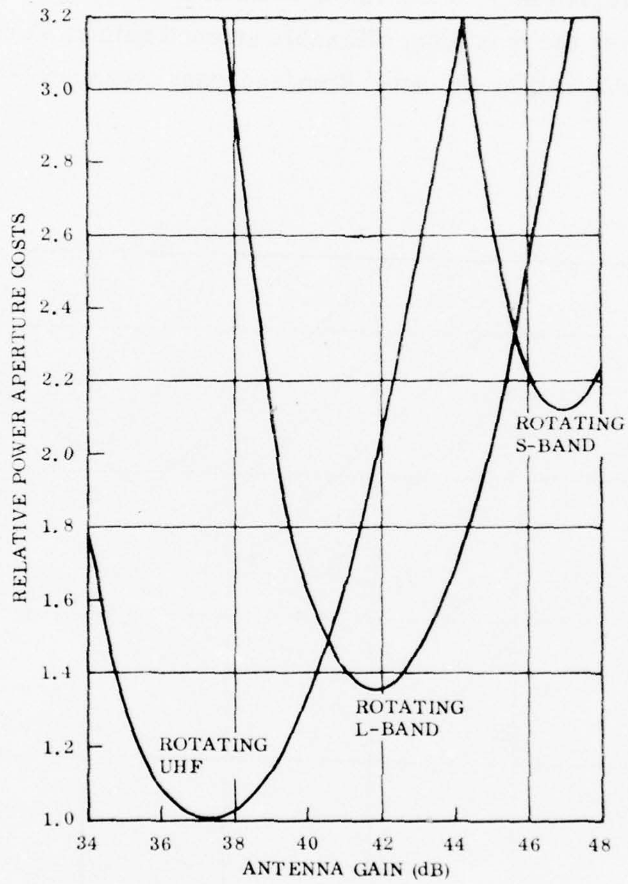

Figure 2-2. 3-D Radar Power Aperture Cost With No Antenna Size Limit

b. FREQUENCY SELECTION

The principal frequency selection criteria is shown in Table 2-1. Based on cost and clutter considerations as the driving functions, operation at Ultra High Frequency (UHF) is preferable. On the other hand, if angular accuracy, multipath, aperture size, and/or bandwidth are the driving functions, S-Band is preferable. L-Band, as may be expected, is a compromise between the two for all cases.

For the 3-D radar, clutter performance and cost are more critical driving the choice towards the lower frequencies.

c. ANTENNA CONFIGURATION

The relative merits of rotating and fixed antenna systems were evaluated in terms of implementation, bandwidth, and frequency.

In the case of the mechanically rotating antenna, a practical limit for the size of minimally-attended rotating antennas is constrained by the goal of fitting inside a standard 55-ft radome. As the azimuth beamwidth is limited between the azimuth resolution of 3° and the beamwidth required to scan the volumetric coverage in the required frame time, the antenna width between these limits may be determined as a function of frequency as shown in Figure 2-3. The aperture width at UHF makes it undesirable for use with a rotating antenna. Based on all of the above considerations the choice in the candidate system narrows down to a rotating L-Band antenna vs a fixed UHF antenna.

d. PENCIL BEAM VS STACKED BEAM CONSIDERATIONS

The total energy required on target in a scan is essentially independent of the use of a pencil beam or stacked beam. This is true for both detection and angular measurement requirements and is a result of the SNR required for detection or measurement being nearly the same for both cases. In the case of the pencil beam, the SNR must be obtained by illuminating the target with sufficient energy in a single transmission. Using stacked beams, the energy per pulse may be reduced by the number of transmissions that illuminate the target, assuming coherent integration of returns.

TABLE 2-1. PRINCIPAL FREQUENCY SELECTION CRITERIA

	UHF	L-Band	S-Band
Power-Aperture Costs	Low	Moderate	High
Aperture Size	Large	Medium	Small
Angular Accuracy	Limited	Good	Excellent
Bandwidth	Narrow	Moderate	High
Clutter Amplitude	Low	Medium	High
Clutter Spectrum	Confined	Reasonable	Broad
Clutter Processing	Doppler Filter and/or MTI	Doppler Filter	Bandwidth, MTI, and/or Circular Polarization
System Noise Temperature	Low	Medium	High
Multipath Performance	Fair	Good	Excellent

As previously discussed, the aperture area, or gain, is essentially sized by the azimuth resolution, height measurement, and scan time requirements, and will be substantially the same for both cases. The reduction in energy per pulse for the stacked beam case may, therefore, be provided by reducing the per pulse transmitter energy in the beam. The limitation on scan time, and beamwidth for the case of the pencil beam, limits the examination of a target during a scan time to approximately 2 looks/scan. For the stacked beam radar, assume that eight beams are formed. This provides enough time for the two bursts of eight pulses (each burst on a different Pulse Repetition Frequency (PRF)). The transmitter power in each beam may be reduced by 9 dB, but since the transmit beam must encompass all eight receive beams, the total transmitted power per transmission is equal to that used by the pencil beam system. There is, therefore, no advantage from an energy viewpoint to either system. The major differences are in the signal processing, implementation, and relative costs of the two schemes.

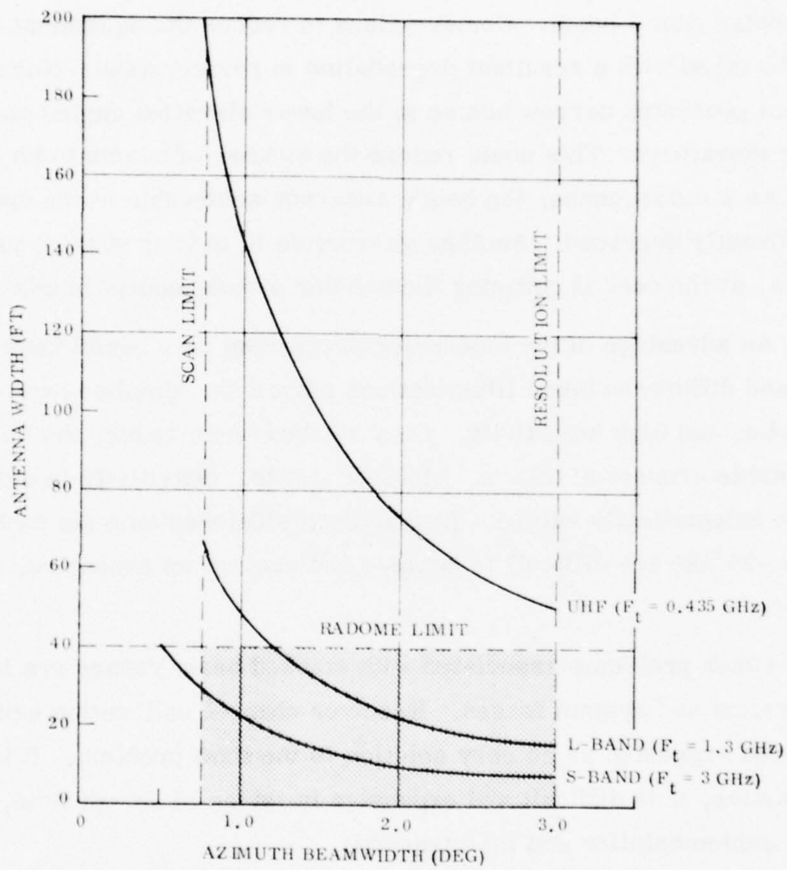

Figure 2-3. Antenna Limits for Candidate Frequency Bands

The stacked beam system requires an intricate beam forming matrix, separate receivers and signal processors for each beam, and a complex rotary joint to handle the total number of beams. In terms of relative costs, processing eight stacked beams with full capability clearly requires more equipment than processing a three-channel monopulse pencil beam. Compromises to reduce the equipment content, of course, may be taken with a resultant degradation in performance. Normally, a stacked beam system generates narrow beams at the lower elevation angles and broad beams at the upper elevations. This could reduce the number of beams to be processed to perhaps six. As a consequence, the height accuracy achievable at the upper elevations is significantly degraded. Another alternative is to time share a processor between beams, at the cost of reducing the number of independent height samples available.

An advantage of the monopulse processing on a pencil beam is that independent sum and difference beam illuminations permit the simultaneous achievement of low sidelobes and high sensitivity. On a stacked beam radar, the beams are designed for acceptable crossover loss and sidelobe levels. Sensitivity is a parameter which cannot be independently varied. Low antenna sidelobes on a stacked beam antenna (e.g., below -25 dB) are difficult to achieve and require an expensive, complex beamforming system.

Other problems associated with stacked beam radars are in receiver channel calibration and system losses. Receiver channel calibration using pilot pulse signals has been suggested as an easy solution to the first problem. It is easy only in concept. In practice, it is difficult and expensive in terms of design time, reliability, hardware implementation and maintenance.

System losses for the stacked beam system due to the inevitable processing losses associated with coherent integration and losses in the beamforming matrix should result in slightly higher total losses for the stacked beam with respect to the pencil beam.

e. PENCIL BEAM VS STACKED BEAM SIGNAL PROCESSING

A major difference between the stacked beam and pencil beam approaches lies in the applicable signal processing. The pencil beam is generally restricted to using a Moving Target Indicator (MTI) signal processing approach due to the limited number of hits available. On the other hand, the stacked beam is generally restricted to a Doppler filter processor if the benefits of coherent processing are to be realized. To fully evaluate the desirability of either the stacked beam or pencil beam approaches, the two forms of signal processing must be evaluated.

With a maximum detection range of 200 nmi, the waveforms and processing used to detect long-range targets are certainly different from the anticlutter waveforms used to detect targets at shorter ranges. This is equally true for either a stacked beam radar or a scanning-pencil beam radar.

Rain clutter at 100 to 125 nmi is subject to wind shear which may be expected to spread the return Doppler over 150 Hz at L-Band. This broad Doppler spread drives the anticlutter waveform, either MTI or pulse Doppler, to a high PRF. A PRF of about 500 Hz, corresponding to an interpulse range of 150 nmi, is the minimum which could be used without seriously compromising the capability of any clutter suppression scheme. A PRF of about 750 Hz, corresponding to an interpulse range of 100 nmi, is much better. For both the stacked beam and the pencil beam radar, a separate waveform with a longer interpulse period and more energy per pulse is required to achieve long-range detections.

A problem common to both a Doppler filter bank and an MTI is "blind speeds". The problem can be made less severe by the use of multiple or staggered PRF's. Consider a Doppler filter-type waveform appropriate in response to rain clutter, consisting of perhaps 8 pulses at 500 Hz PRF. Two waveforms are transmitted at different PRF's and each is processed in an 8-pulse Doppler filter bank. Figure 2-4 indicates the frequency responses of the 8 Doppler filters for each of the two waveforms. Each filter has a periodic response with the period equal to the PRF. Each filter bandwidth is roughly one-eighth of the PRF. If clutter around zero Doppler is present, it will be passed by filter No. 1. In such an event the output of filter No. 1 is discarded. But because of the filter periodicity, target returns at Dopplers around

integer multiples of the PRF are discarded as well. This blind speed problem is helped by using two waveforms with PRF's which differ by the filter bandwidth. As shown in Figure 2-4, the first blind speeds do not overlap, so a target return at the blind speed of either waveform will be detected by the other waveform.

However, not all blind speeds are eliminated. Every seventh blind speed of the higher PRF (500 Hz) coincides with every eighth blind speed of the lower PRF (437.5 Hz). Hence, blind speeds exist at integer multiples of 3500 Hz. An aircraft flying at Mach 3 will experience a Doppler shift of over 8 kHz. Hence, if velocity coverage to ± Mach 3 is required, Doppler filter processing will result in four blind speeds.

This problem is even more severe when weather clutter is present, when wind shear may be expected to spread the weather return Doppler over 150 Hz or more. This is illustrated in Figure 2-5 where it may be seen that three filter outputs (Nos. 8, 1, and 2) contain clutter. Therefore, three-eights of all target Dopplers are masked by clutter. Using two waveforms at different PRF's will not help the situation appreciably. A simple MTI, of course, also has the disadvantage of containing blind speeds at target Dopplers that are multiples of the PRF. A staggered PRF can eliminate the blind speeds, but the resulting filter may still contain deep notches at many target velocities. This problem is greatly reduced by the use of multiple stagger codes. Although no MTI stagger code totally eliminates near blind speeds within the pass band, different stagger codes yield different low response points. Hence, by transmitting and processing two MTI waveforms with different stagger codes, either in the same beam position or at adjacent beam positions with a high-beam packing density, it is possible to maintain near uniform sensitivity vs frequency.

(1) <u>Ground Clutter Rejection</u>

For ground clutter the radar altitude of 4500 ft (the highest specified) gives the most severe requirements. The radar horizon is 83 nmi distant and can contain ground clutter for the full extent. If the area is mountainous with similar 4500-ft peaks, the beam could contain ground clutter to ranges of 165 nmi. For purposes of this design, the ground clutter reflectivity will be considered to be constant to 120 nmi and then drop off at a rate of 12 dB/octave beyond that range.

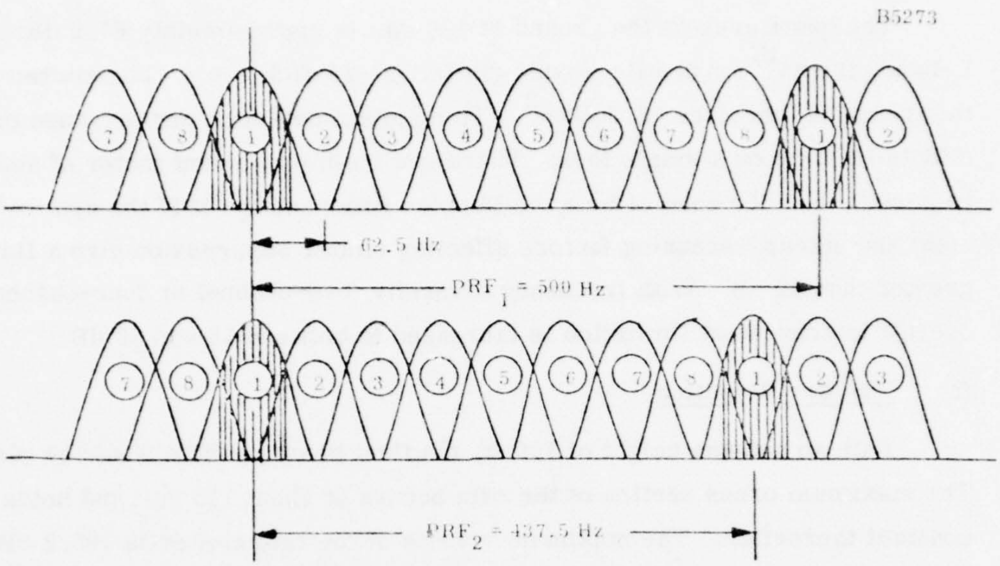

Figure 2-4. Doppler Filter Responses at Two PRF's

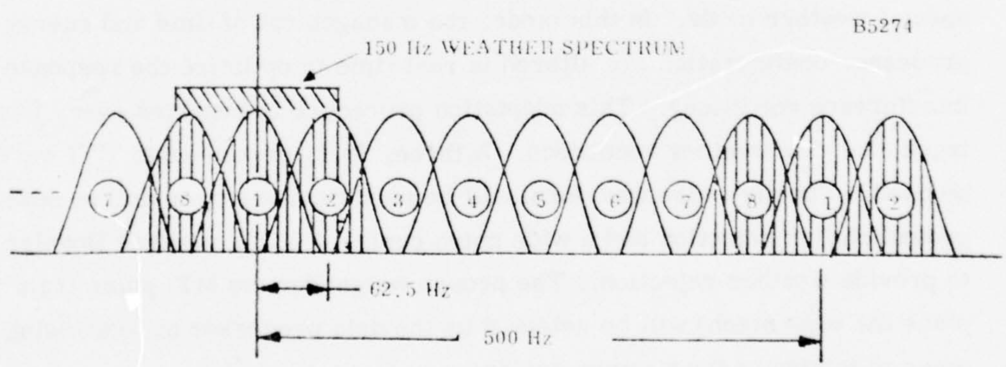

Figure 2-5. Doppler Filter Responses to a Spread Weather Spectrum

The beam area on the ground at 120 nmi is approximately 67.2 dBm^2. At L-band, the 84th percentile ground clutter is -24 dBm^2/m^2. The clutter return at this range is therefore 43.2 dBm^2. To maintain detection performance the required SNR is 10.5 dB on a single look. Therefore an improvement factor of about 54 dB is required. For the case of both the Doppler filter and the MTI the applicable equipment and antenna-scanning factors affecting clutter suppression give a limitation of greater than 49 dB. With frequency diversity (two-channel or four-channel), the overall improvement limitation is increased to between 55 and 59 dB.

(2) Weather Rejection

With an antenna height of 100 ft, the first beam position would be placed at 0.8°. The maximum cross section of the rain occurs at about 115 nmi and holds essentially constant thereafter. The maximum volume of the rain clutter is 105.2 dBm^3. The reflectivity of the rain clutter at L-band for 15 mm/h rain is -87.9 dBm^2/m^3. Therefore, the clutter cross section is 17.3 dBm^2. To maintain the desired performance, a 30 dB improvement is needed.

The Doppler filter, for a target not located in a clutter-filled filter, will easily provide the required 30 dB. Using two PRF's the target that competes with clutter may normally be shifted, to a nonclutter-filled filter limited per the earlier discussion on this subject.

When confronted with weather, the MTI radar operates more effectively in a special weather mode. In this mode, the management of time and energy and the MTI processor configuration are altered in real time to optimize the response to changing interference conditions. This adaptation procedure is repeated every five minutes to track changing weather conditions. A three, four, or six-pulse MTI waveform will be used. The six-pulse waveform will be used to give a deep null at zero velocity for ground clutter rejection and a wide notch centered at the weather Doppler frequency to provide weather rejection. The proper weight for the MTI pulse train (to properly place the wide notch) will be selected by the data processor by exercising the weather mode to minimize the weather residue.

The average velocity across the beam at 0.8° varies from 0 to 20 m/s at maximum range with a standard deviation of 6 m/s. Therefore, a design notch centered at 10.4 m/s with a width of 20.9 m/s will cover the range of interest. The corresponding frequency domain characteristics are a center frequency of 90.5 Hz, with a width of 181 Hz. A 6-pulse MTI waveform provides a deep null (in excess of 50 dB) at zero Doppler and a broader notch to cover the weather spread with a suppression of 35 dB. The upper beams which do not contain ground clutter will provide adequate suppression with three- or four-pulse MTI waveforms.

The notch center and width are adapted to the average clutter velocity to optimize performance by providing a narrower notch, when required, at the proper mean Doppler to maximize clutter rejection. Nonadaptable waveforms would require a notch width of 360 Hz to cover the spread from ±180 Hz, thus degrading performance. The clutter spread of 180 Hz corresponds to 33% of the total unambiguous Doppler at a PRF of 550 Hz. With a Doppler filter implementation this would correspond to blanking three filters in the vicinity of the clutter Doppler.

f. ELECTRONIC COUNTER COUNTERMEASURES (ECCM) IMPLICATIONS

The stacked beam radar with Doppler filter processing operates at a disadvantage in an Electronic Countermeasures (ECM) environment. First, Doppler processing requires long, single-frequency waveforms. This mode of operation seriously compromises the effectiveness of frequency agility and thereby increases the radar's vulnerability to spot or repeater jamming. Second, because the transmit beam is spoiled to cover the total elevation sector, the burnthrough capability is degraded. Finally, on the stacked-beam radar, low sidelobes, a most effective ECCM feature, are very difficult to achieve.

g. PENCIL BEAM VS STACKED BEAM SUMMARY

The stacked beam radar is significantly more expensive than a functionally-equivalent scanning-pencil beam radar. In the antenna, the full beamforming hardware including pillbox reflector and combining matrices (or corresponding array beamformer) for transmitter and receiver as required to achieve high efficiency and low sidelobes is considerably more complex than that for a scanning beam antenna. Multiple receivers and processing channels, as well as MTI's and/or Doppler filter banks implemented on each of the multiple beams, also add considerable expense.

The scanning-pencil beam radar with MTI processing performs satisfactorily in a very heavy clutter environment. The scanning pencil beam radar also has an inherent ECCM advantage. Based on the above considerations, a scanning pencil-beam technique with MTI was selected for the 3-D radar. A three-pulse MTI will be used in those beams where ground clutter is present (usually the two lower beams). Pulse-to-pulse stagger will be used with the MTI, and complementary staggers will be used with two transmissions so that a nearly uniform pass band response will result. In weather clutter, a three-, four-, or six-pulse MTI will be used.

SECTION III

CANDIDATE SYSTEMS

The basic array candidates are a Y-configuration, a cylinder, and rotating planar array. The basic array configuration of a fixed aperture at S-band, L-band, and UHF contain the same number of elements, have the same gains, and are dimensionally related by the ratio of wavelength if designed to the same set of parameters. However, aperture size needs to be considered in conjunction with element cost and the cost of power generation to draw a definite conclusion. The candidate systems are shown in Figure 3-1.

A monopulse pencil beam with an adaptive MTI and zero Doppler moving target detector will be employed with any of the above candidate systems.

1. Y-CONFIGURATION PLANAR ARRAY

A special form of the planar array which allows use of "central row transceivers" is the Y-configuration. The Y allows six faces with only three sets of phase shifters. The transceivers can be switched to the proper "wing" and phase shifters set to select the face. Scan per face is ±30°, with associated loss of 0.6 dB. In addition to the reduced loss, the use of distributed, yet centralized, transceivers is attractive.

At L-band, each array face measures 16.5 ft wide by 24 ft high with integral IFF dipoles. This array may be tower mounted and housed in a 55-ft diameter radome. The same array face at UHF will be 49.5 ft wide by 72 ft . From a practical viewpoint, this eliminates UHF from consideration.

2. CYLINDRICAL ARRAY

The considerations for the selection of the cylinder diameter are the same as those for the 2-D case. The vertical dimension is a function of the desired beamwidth as in the case of a planar array. At UHF, a cylindrical array with a diameter of 64 ft and a height of 59 ft would be required to provide a 3.0° x 2.5° azimuth/elevation beamwidth. Of the 156 columns of dipole elements, 52 columns are selected

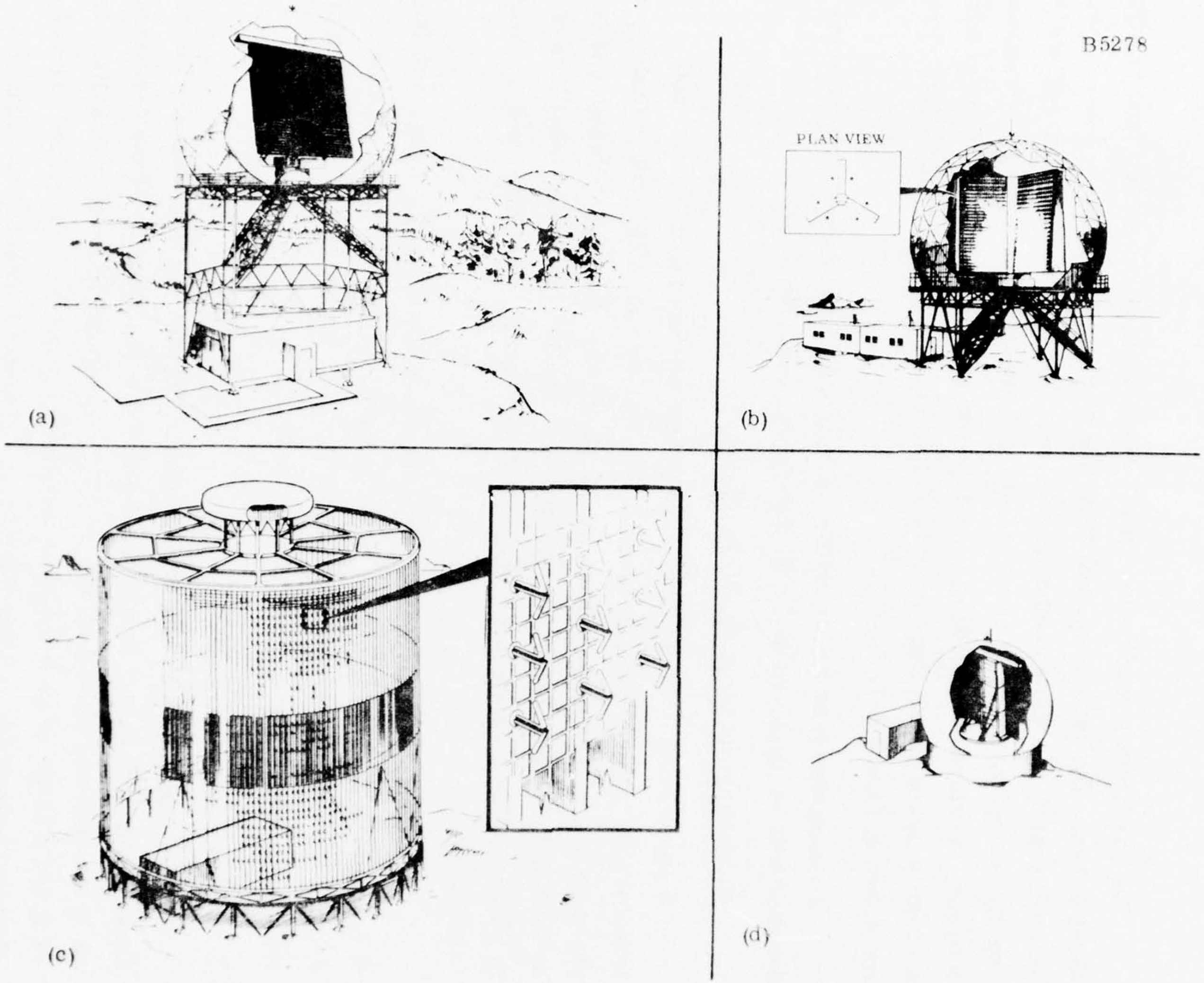

Figure 3-1. 3-D Radar Candidate Approaches

in azimuth, of which 44 are activated at one time. The options for steering the beam in 3-D space are:

- Use one phase shifter per element
- Use a Butler matrix to either form simultaneous beams or select any beam
- Provide one phase shifter per column and frequency steer in elevation

Column transceivers are housed in an enclosed annular ring inside the open frame cylinder wall. Cables from each transceiver feed the 36 dipole elements per array column. The UHF antenna configuration is shown without radome protection because of the large size and the openness of the structure.

3. ROTATING PHASED ARRAY

The final candidate is a rotating phased array. The L-band antenna consists of 44 horizontal passive linear arrays, or row feed networks, stacked one above the other on 6.6-in. centers to make up the 23.2 ft wide by 24.2 ft high planar array. Mounted directly behind each row feed is a distinct, dedicated transmitter-receiver. This configuration is described in more detail in a subsequent paragraph.

The S-band rotating array is housed in a homogeneous foam radome. The 12-ft high array consists of approximately sixty 11-ft long stripline row feeds with integral dipole elements. Solid-state (Traveling Wave Tubes (TWT)) transceivers and phase shifters, feeding each array row, are packaged on the array behind the row feeds. A standard 14-ft long IFF trough antenna is shown mounted on top of the array. A support platform and drive components provide azimuth rotation of the antenna assembly. The size of the S-band antenna system lends itself to foam radome protection. The radome shown measures 28 ft in diameter and is 21 ft high. Factory-produced panels for the radome are "foam-welded" together in the field, forming a homogeneous structure with excellent RF transmission properties. The assembled radome can be emplaced over the antenna onto a concrete base ring by a crane or helicopter. The remaining electronics can be housed in the radome/antenna base structure or in a factory-assembled shelter module.

4. CANDIDATE COST CONSIDERATIONS

For a fixed array vs a rotating array, the number of elements in azimuth must increase because scanning in azimuth is required ($d = 0.88\lambda$ versus 0.57λ). A phase shifter per element, or some form of row/column steering is needed. The total number of elements required for the cylindrical array is 4.4 times that required for a rotating array, and 6 times the rotating array for the Y-configuration. The feed systems and feed system losses are also both higher for the fixed arrays. A comparison of cost among the three candidates all implemented at UHF is shown in Figure 3-2. The large cost discrepancy between the rotating and fixed system was a primary factor in selecting a rotating system as the baseline system. Included in the figure for comparison are the rotating L-band and rotating S-band systems.

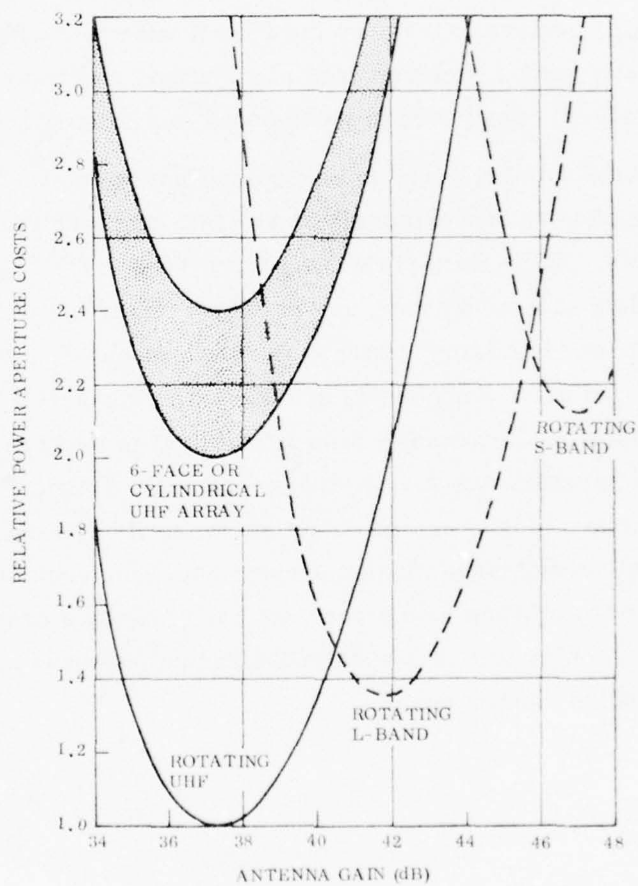

Figure 3-2. 3-D Radar Power Aperture Cost

SECTION IV

MINIMALLY-ATTENDED 3-D RADAR BASELINE CONFIGURATION

1. RADAR CONFIGURATION - 200 nmi RANGE

The rotating array at L-band is recommended which utilizes currently available technology. An aperture 24.2 x 23.2 ft, with a peak power of 36.5 kW, (tapered to give a peak transmit sidelobe of -20 dB, if required) will provide the desired performance. Four diversity channels at long-range and subsequent reductions in processing channels as a function of elevation angle (reduced range requirements) to a minimum of two channels will minimize the duty factor to maximize reliability. At ranges of 100 nmi and less, a 20 μs pulse is used with four- or two-channel diversity (range dependent). The block diagram of Figure 4-1 shows the baseline configuration.

2. OPERATIONAL CONCEPT

The 3-D radar will operate as a sensor providing three-dimensional radar and IFF data to a remote center. A radar operator per site is not required and, in fact, an operator's display console is not provided in this configuration. All radar and IFF video, digital data on detected targets, and control and status signals required to operate the radar are remoted.

A maintenance console is incorporated. It includes a Plan Position Indicator (PPI) display with readouts and controls adequate to permit accurate assessment of radar output data quality, and an alphanumeric Cathode Ray Tube (CRT) terminal for communicating detailed performance status and fault location data. The CRT terminal is also the man/machine interface through which system initialization and infrequent operational parameter changes are accomplished.

The array may be operated unattended. Its performance is automatically and continuously monitored at the Processing Center to assure corrective maintenance when required. Array reliability is high enough to assure proper operation with maintenance actions (either corrective or preventive) at intervals of not less than one to two months. Because of the high degree of redundancy provided by the distributed electronics, emergency corrective maintenance on the array will be required only rarely.

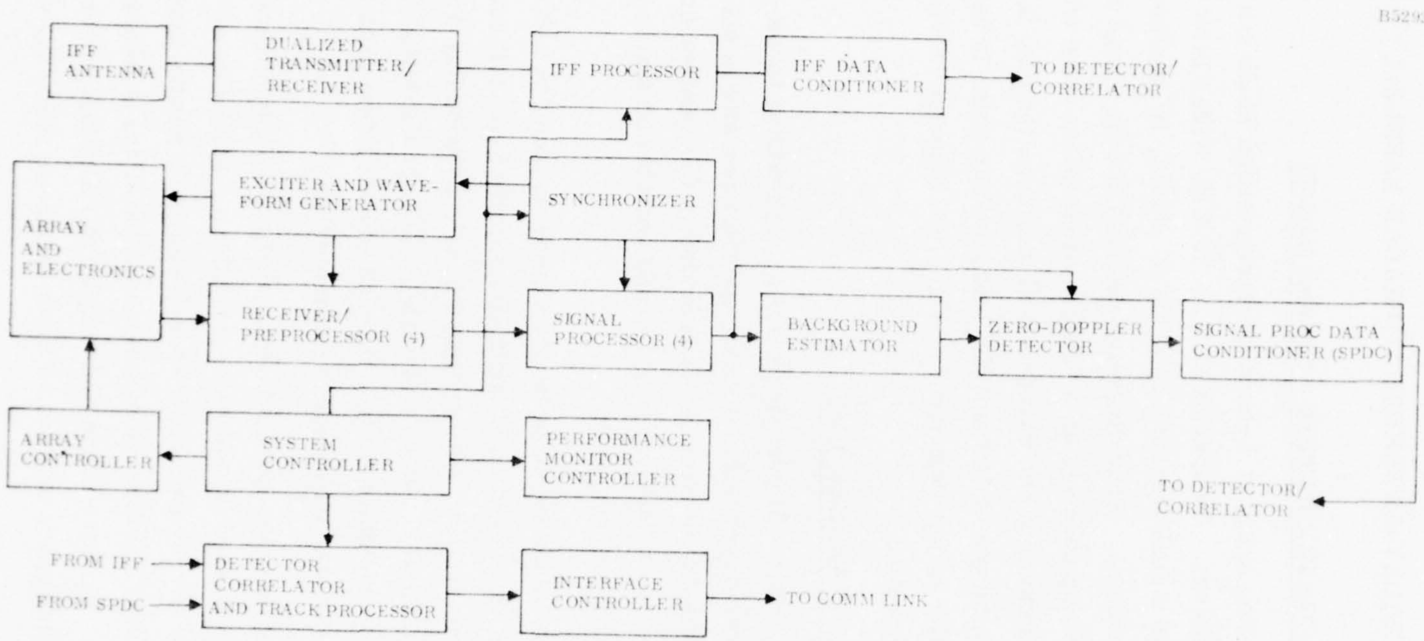

Figure 4-1. 3-D Radar Overall Block Diagram

SECTION V

OPERATIONAL PARAMETERS

1. OPERATING FREQUENCY

The system operates over the 14% frequency band from 1215 MHz to 1400 MHz. The transmit frequency may be varied through a fraction of that band or over the entire band on a pulse-to-pulse basis. The radar may also be operated at a single fixed frequency anywhere within that band.

2. FIELD DEGRADATION FACTOR

The radar performance in terms of detectability and position estimation accuracy is calculated with a 2-dB loss invoked to reflect the degradation in sensitivity which could accumulate over the long period of operation between maintenance cycles. Thus, during the period through which actual system losses are less than 2 dB, the radar performance exceeds specified limits.

3. COVERAGE

The system detects and locates in range, height, and azimuth up to 100 targets within each 12-s scan and within the surveillance volume bounded by the limits: 5 to 200 nmi in range, up to 25° in elevation, 100 kft in altitude, and 360° in azimuth. These targets are, typically, small fighter aircraft flying at speeds as high as 2400 kts. Detectability is maintained on target returns immersed in a background of strong clutter, including terrain or sea clutter and weather (i.e., rain or snow). In those azimuth cells containing weather clutter, in order to maintain target detectability, the range coverage may be reduced to 150 nmi. However, the 200 nmi coverage is maintained at all azimuths void of weather clutter.

4. DETECTABILITY

While maintaining a false-alarm rate not in excess of 3 per 360° azimuth scan, the radar will achieve a detection probability (on 1 m^2 fluctuating targets) of at least 90% at ranges from 5 to 200 nmi. A detection range calculation is provided in Figure 5-1. A detailed explanation of the parameter values used in this calculation is given in Section VIII.

1. Compute the system input noise temperature T_s, following the outline in section A below.
2. Enter range factors known in other than decibel form in section B below, for reference.
3. Enter logarithmic and decibel values in section C below, positive values in the plus column and negative values in the minus column. For example, if $V_{0(dB)}$ as given by Figs. 4 through 9 is negative, then $-V_{0(dB)}$ is positive and goes in the plus column. For C_B, see Figs. 1 through 3. For definitions of the range factors, see Eq. (13).

Radar antenna height: h = ft. Target elevation angle: θ = °. (See Fig. 13.)

A. Computation of T_s:

$T_s = T_a + T_r + L_r T_e$

(a) Compute T_a.
For $T_{tg} = T_{ta}$ = 290 and T_g = 36 use Eq. (37a).
Read T_a' from Fig. 11.

$L_{\alpha(dB)}$: ______ L_a: ______

$T_a = (0.876\,T_a' - 254)/L_a + 290$

T_a = °K

(b) Compute T_r using Eq. (40).
For T_{tr} = 290 use Table 1.

$L_{r(dB)}$: ______ T_r = °K

(c) Compute T_e using Eq. (41) or using Table 1.

$F_{n(dB)}$: ______ T_e: ______ °K

L_r: ______ $L_r T_e$ = °K

Add. T_s = °K

B. Range Factors		C. Decibel Values	Plus (+)	Minus (-)
$P_{t(kW)}$	36.5	$10 \log P_{t(kW)}$	15·62	.
$\tau_{\mu sec}$	160	$10 \log \tau_{\mu sec}$	22·04	.
G_t		$G_{t(dB)}$	39·59	.
G_r		$G_{r(dB)}$	39·59	.
$\sigma_{(sq\,m)}$	1	$10 \log \sigma$	.	.
f_{MHz}	538.6	$-20 \log f_{MHz}$	.	62·28
T_s (°K)		$-10 \log T_s$	.	27·31
V_0		$-V_{0(dB)}$	.	10·51
C_B		$-C_{B(dB)}$	.	2·10
L_t		$-L_{t(dB)}$	.	1·05
L_p		$-L_{p(dB)}$	.	·85
L_x		$-L_{x(dB)}$	.	3·00
Range-equation constant (40 log 1.292)			4.45	
4. Obtain the column totals →			121.29	107.10
5. Enter the smaller total below the larger →			107.10	.
6. Subtract to obtain the net decibels (dB) →			+14·19	- .

7. In Table 2 find the range ratio corresponding to this net decibel (dB) value, taking its sign (±) into account. Multiply this ratio by 100. This is R_0 → 226.35

8. Multiply R_0 by the pattern-propagation factor F = (see Eqs. (42) through (65) and Figs. 12 through 19): $R_0 \times F = R'$ → 226.35

9. On the appropriate curve of Figs. 21 and 22 determine the atmospheric-absorption loss factor, $L_{\alpha(dB)}$, corresponding to R'. This is $L_{\alpha(dB)(1)}$. → 2.15

10. Find the range factor δ_1 corresponding to $-L_{\alpha(dB)(1)}$ from the formula $\delta = \text{antilog}\,(-L_{\alpha(dB)}/40)$ or by using Table 2. → 0.884

11. Multiply R' by δ_1. This is a first approximation of the range R_1. → 200

12. If R_1 differs appreciably from R', on the appropriate curve of Figs. 21 and 22, find the new value of $L_{\alpha(dB)}$ corresponding to R_1. This is $L_{\alpha(dB)(2)}$. →

13. Find the range-increase factor (Table 2) corresponding to the difference between $L_{\alpha(dB)(1)}$ and $L_{\alpha(dB)(2)}$. This is δ_2. →

14. Multiply R_1 by δ_2. This is the radar range in nautical miles, R. → 200

Note: If the difference between $L_{\alpha(dB)(1)}$ and $L_{\alpha(dB)(2)}$ is less than 0.1 dB, R_1 may be taken as the final range value, and steps 12 through 14 may be omitted. If $L_{\alpha(dB)(1)}$ is less than 0.1 dB, R' may be taken as the final range value, and steps 9 through 14 may be omitted. (For radar frequencies up to 10,000 megahertz, correction of the atmospheric attenuation beyond the $L_{\alpha(dB)(2)}$ value would amount to less than 0.1 dB.)

Figure 5-1. Pulse-Radar Range-Calculation Work Sheet*
(Based on Equation (13))

* A Guide to Basic Pulse-Radar Maximum-Range Calculation by L. V. Blake, December 23, 1969, NRL Report 6930.

** 1-dB radome loss plus 2-dB field degradation factor.

5. ACCURACY

The accuracy of the height estimates made on all detected targets at elevations of 0.8° or above will be at least 2000 ft at a range of 100 nmi.

The root-mean-square (rms) error in the azimuth estimate made on all declared targets will not exceed 0.3°.

The range of detected targets will be determined with an rms error not in excess of 1500 ft.

Two aircraft separated by 2.25° in azimuth or 2.15° in elevation are resolvable, in that they are detectable as distinct targets with a probability of 50%. Two targets separated in range by 0.5 nmi will be resolved with a probability of better than 99%.

SECTION VI

RELIABILITY

1. MTBF

The mean-time-between-failures (MTBF) of the system will be a minimum of 1000 h. The prime power generation and air conditioning as required to cool the processor electronics and the IFF subsystem are excluded from this reliability specification.

Relevant failures as defined for the purpose of calculating MTBF are those accumulations of equipment faults which cause the loss or significant degradation of a major tactical function. Table 6-1 indicates tolerable system losses; that is, losses which do not constitute system failures. Losses not specifically exempted therein do constitute failures.

2. DESIGN PHILOSOPHY

The radar will be designed for gradual performance degradation in order to minimize radar downtime as a result of failure of a single or small number of hardware components, for example:

1. Row transceivers may have multiple failures with little impact on overall system performance.

2. Sum (Σ), elevation - difference (Δ El), azimuth - difference (Δ Az), and sidelobe blanker (SLB) channel switching will take place at the front end of the final receiver and at the output of the digital MTI's to provide primary channel redundancy.

3. The digital processor will degrade gradually in the face of Printed Wiring Board (PWB) failures by virtue of its multiple channel configuration.

4. In case of computer failure, the radar will operate in a backup 2-D mode (a failure in a reliability sense, but not totally in an operational sense).

5. The Processing Center equipment will operate without conditioned air for a period of 30 minutes during 90% of the expected environmental conditions.

TABLE 6-1. TOLERABLE SYSTEM LOSSES (RELATIVE TO MTBF CALCULATIONS ONLY)

Function/Equipment	Acceptable Condition
Sensitivity	Up to 2-dB degradation
Transmitter Frequency Source	Three-fourths or more of the available transmit frequencies
Row Transceiver/Power Supplies	Losses acceptable as long as system performance does not degrade more than 2 dB
Performance Monitoring Equipment	Failures are relevant only when their failure prevents determination of degradation in system performance
Fault Location Equipment	Fault isolation or location equipment that fails and has no adverse operational effect on system performance is an acceptable loss
Prime Power and Air Conditioning	Not relevant
IFF Equipment	Not relevant
Σ, ΔEl, ΔAz, or SLB Processor Channel	Loss of one of these channels is permissible if, in the event of a Σ or ΔEl or ΔAz channel failure, the failure is automatically detected and the SLB channel is automatically pre-empted to continue providing the functions of the three primary channels
Display Console	Not relevant, since console is used for maintenance purposes only

SECTION VII

MAINTAINABILITY

1. MAINTAINABILITY REQUIREMENT

The Mean-Time-To-Repair (MTTR) shall be 50 minutes, using the equipment and personnel available at the radar site. This calculation excludes maintenance of the IFF, air conditioning, and power generation equipment.

2. DESIGN PHILOSOPHY

Performance monitoring features are essential to assist the field operators in fault isolation. Each major subassembly and element of performance is automatically and continuously, monitored during operation. Quantitative system performance data is available via an alphanumeric CRT terminal. Status on a go/no go basis is clearly indicated on a performance monitor status display (PMSD).

The radar is designed so that automatic fault location to the lowest echelon is realized with a practical computer-aided approach.

On-site maintenance may be accomplished using no more than a three-man maintenance team, consisting of two personnel capable of repairing failures by remove-and-replace techniques (equivalent to USAF Skill Level 3) and one technician capable of performing maintenance using an oscilloscope, power meters, and other simply-operated standard test equipment (equivalent to a USAF Skill Level 5). A remove-and-replace procedure will be sufficient in 95% of all required maintenance actions.

Adequate spares to service the equipment will be provided on-site. The technicians will repair failures in the system at the PWB or assembly level.

3. MAINTENANCE DESIGN FEATURES

Table 7-1 depicts several of the more important maintenance features incorporated in the design.

TABLE 7-1. MAINTENANCE DESIGN FEATURES

1. Replacement of PWB modules can be made with power-on with no deleterious effects.

2. Replaceable modules are safely handled by one man.

3. Fault location is accomplished automatically to the following typical number of Least Replaceable Units (LRU's).

Digital PWB	1 or 2
Analog PWB	1 or 2
Array LRU's	1

4. Hardware adjustments are held to an absolute minimum during normal operation or after a system failure.

5. No special handling equipment is necessary to perform repairs.

6. No major electronic parts, excepting display tubes, are life limited.

7. All major repairs can be accomplished at the site using site personnel.

8. Quick and easy access to all equipment is possible using standard tools.

9. The assemblies and subassemblies of the equipment are mechanically and electrically interchangeable with other identical assemblies and subassemblies.

4. MAINTAINABILITY ALLOCATIONS

Table 7-2 shows the maintainability allocations to the major radar subsystems.

TABLE 7-2. MTTR ALLOCATIONS

	Subsystem/Unit	MTTR in Minutes
1.	Row Transceivers	35
2.	Ancillary	50
3.	Final Receiver	50
4.	Exciter	45
5.	Platform Logic/PS	35
6.	Preprocessor/Waveform Generator	35
7.	Digital Signal Processor	35
8.	Data Processing Hardware	35
9.	Computer	40

5. PERFORMANCE MONITOR

a. FAULT DETECTION PROBABILITY

The automatic PM process shall detect at least 95% of all failures which result in a significant performance degradation. Generally speaking, a significant performance degradation involves a loss in either sensitivity or accuracy of at least 2 dB, a reduction in clutter suppression of at least 6 dB, some degree of reduced data transfer capability, or the loss of major ECCM function (if included).

b. TIME TO FAILURE DETECTION

The mean and maximum time intervals between a hard failure and the indication thereof on the CRT shall not exceed 30 seconds and 2 minutes, respectively.

c. DUTY FACTOR

The time taken by the PM procedure to run scheduled PM tests or to perform any other operation which reduces the available operational time shall be limited to 8% in the normal mode and 6% in the weather mode.

d. REDUNDANCY IMPLEMENTATION

The automatic PM procedure shall have the capability to isolate a fault to the Σ, ΔAz, or ΔEl channel in the final receiver, preprocessor and/or digital processor input stages (through the MTI), and to activate the built-in hardware capability to use the redundant SLB channel. Data rerouting shall continue so long as the failure persists.

SECTION VIII

RADAR CHARACTERISTICS

1. RADIATED POWER

In the "full-up" condition, the radar will operate with a radiated peak power (averaged over frequency and temperature) of not less than 28.7 kW. Under worst case temperature and frequency conditions (i.e., anywhere within the 10% frequency band and -62 to +38°C temperature range) the radiated power will not decrease by more than 0.5 dB. This radiated power level is the result of the following hardware characteristics:

Power delivered to circulators	36.5 kW
Ohmic loss in circulators, RF filters, cables, and connectors	0.40 dB
Row feed ohmic and mismatch losses	0.65 dB

2. TRANSMIT GAIN

The transmit gain at band center (1308 MHz) will not be less than 39.59 dB. This gain is the result of the following hardware characteristics:

Transmit area gain	40.67 dB
Row feed taper efficiency	-0.93 dB
Row to row amplitude and phase mismatches	-0.15 dB

3. BEAMFORMING AND STEERING REQUIREMENTS

The radar antenna subsystem will generate a transmit sum beam; a receive monopulse set including sum, azimuth difference, and elevation difference beams, and a receive low-angle squinted sum beam pair. These beams will be phase-steered in elevation to provide the following beam repertoire:

1. Two complete sets of beam patterns to service the normal and weather modes. Each set can be incremented in elevation in 0.25° steps to ±2° by operator selection, and any beam within these sets can be generated at any one of the 16 operating frequencies across the 10% agile band.

2. Two phase-spoiled beams for lower and upper sector coverage in the weather adaptation procedure.

3. An approximate csc^2 beam for use in the Emergency 2-D Mode.

4. RECEIVE AREA

The effective receive area, including taper efficiency and row-to-row amplitude and phase differences, will not be less than 15.04 dBm^2 for the monopulse sum beam and 15.62 dBm^2 for the low-angle sum beam.

5. SIDELOBE LEVELS

The Y99 sidelobe levels (the level which is exceeded by 1% of the sidelobes throughout visible space) will not exceed the following values relative to the peak sum beam response:

Beam Designation	Principal Elevation Axis (dB)	Principal Azimuth Axis (dB)	Off Axis (dB)
Transmit	-25	-25	-50
Receive Monopulse Sum	-25	-25	-50
Azimuth Difference	-50	-20	-45
Elevation Difference	-20	-50	-45
Low-Angle Lower Sum	-13	-25	-38
Low-Angle Upper Sum	-20	-25	-45

6. ANGULAR SENSITIVITY

The angular sensitivity, as measured by the slope of the delta-to-sum beam ratio at boresight, will be 0.043 volts of delta/volt of sum/mrad in elevation.

7. BEAM POINTING ERRORS

Uncertainty in the beam pointing angle translates directly to an error in the estimation of target angular position. In the 3-D Radar, the beam pointing uncertainty will not exceed an rms value of 0.19 msin in azimuth, 0.44 msin in elevation when the low-angle beam pair is used, and 0.56 msin in elevation when the monopulse set is used. These errors derive from a number of sources, as summarized below:

	Low-Angle Elevation rms Error (msin)	Monopulse Elevation rms Error (msin)	Azimuth rms Error (msin)
Row Feed Amplitude and Phase Errors	0.05	0.15	0.10
Row Receiver Amplitude and Phase Errors	0.30	0.45	
Column Feed Amplitude and Phase Errors	0.20	0.15	
Uncorrected Scanning with Frequency	0.05	0.05	0.05
Uncorrected Scanning with Temperature	0.20	0.20	
Array Orientation Uncertainty	0.15	0.15	0.15

8. ERROR IN LOCATING TARGET RE: BORESIGHT

The rms errors in the estimate of arrival angle relative to the beam pointing angle will not exceed 1.19 msin in elevation when the low-angle beam pair is used, 0.64 msin in elevation when the monopulse set is used, and 0.62 msin in azimuth. These errors derive from a number of sources, as summarized below:

	Low-Angle Elevation rms Error (msin)	Monopulse Elevation rms Error (msin)	Azimuth rms Error (msin)
Beam Shape Uncertainty	0.05	0.05	0.05
Final Receiver Channel Mismatches	0.50	0.25	0.25
Slip Ring Channel Mismatches	0.10	0.10	0.05
Signal Processor Channel Mismatches	0.50	0.25	0.25
Signal Processor Quantization Noise	0.50	0.50	0.50
Monopulse Calculation Error	0.10	0.10	0.10
Multipath (Reflection Coefficient = 0.5)	0.80	0.10	--

9. HEIGHT CALCULATION

Target height is determined using radar estimates of height, range, and elevation angle and is based on the Central Radio Propagation Laboratory (CRPL) Reference Radio Refractivity Atmosphere Model and the radar site value of surface refractivity (N_s). Implementation of the height calculations (neglecting radar errors, errors in N_s, and refractivity model errors) will be accurate to less than 100 ft at 100 nmi.

10. SYSTEM NOISE TEMPERATURE

The system noise temperature, referenced to the row feed output and in the 0 dB Sensitivity Time Control (STC) condition, will not exceed 538.6°K when the low-angle beam pair is used and 516.1°K when the elevation monopulse beam pair is used. Included in this temperature are the contributions of sky noise, array and receiver ohmic losses, and preamplifier noise temperature as follows:

	Unit Temp (°K)		Noise Gain (dB)		Cumulative Temp (°K)	
Sky and Ground Noise	120°				91	
Radome and Row Feeds	92.3°		-1.2		161	
Row Receivers	324		18.8		485	
Column Feed	870*	435**	-6*	-4**	496.5*	490.7**
Final Receiver	766		41		538.6*	516.1**

* Low-Angle column feed
** Elevation monopulse column feed

11. SIGNAL PROCESSING LOSSES

The loss in sensitivity due to nonideal processing in the signal processor will not exceed 1.85 dB in the short-range interval (i.e., from 5 to 100 nmi) and 2.1 dB in the long-range interval (from 100 to 200 nmi). This loss is made up of the following factors:

	Long-Range Interval	Short-Range Interval
Additive Preprocessor Noise	0.04	0.06
Quantization Noise	0.60	0.35
Pulse Compression (P/C) Filter Frequency Mismatch	0.16	0.08
Range Sampling	0.35	0.35
Normalization	0.02	0.10
Sidelobe Blanking	0.10	0.10
Weighting to Achieve 28 dB Range Sidelobes	0.65	0.65
Mismatch Filtering	0.04	0.04
Approximation to Magnitude	0.10	0.10

12. CLUTTER CANCELLATION

The clutter-to-signal ratio (CSR) improvement will be at least 50.1 dB against ground clutter and 34.2 dB against heavy weather clutter. The improvement factor is defined to be the signal-to-clutter ratio (SCR) after MTI and pulse compression, relative to the SCR which would result by simply pulse-compressing the 1.25 MHz bandwidth pulse. The improvement factor is limited by a number of factors, as follows:

Limiting Item	Improvement Factor Limitation (dB)	
Waveform Generator Stability	60	60
Local Oscillator (LO) Stability	60*	46**
Row Transceiver Stability	58	58
Slip Ring Stability (Round Trip)	69	69
Analog-to-Digital (A/D) Converter (9 Bits)	53	53
MTI Null Depth	56	
Clutter Spread (Including Antenna Motion)	65*	35**
Totals	49.3	34.6

* Ground Clutter at 20 nmi
** Weather Clutter at 100 nmi

SECTION IX

METHOD OF OPERATION

1. TIME/ENERGY MANAGEMENT

The 3-D Radar operates in any one of the following three modes according to operational requirements and threat conditions:

1. Normal mode
2. Weather mode
3. Emergency 2-D mode

The sequence of operations and time/energy management doctrine employed in each mode are described below.

a. NORMAL MODE OF OPERATION

The 5- to 200-nmi range interval to be searched is divided into short and long-range intervals, the former extending from 5 to 100 nmi and the latter extending beyond the short-range interval to the coverage envelope limit. The elevation scan beam schedule is described in Figure 9-1. Eighteen beam positions, five in the long-range interval and thirteen in the short-range interval, are utilized. The beam boresight angles shown in Figure 9-1 may be (electronically) elevated or depressed in 0.25° increments to ±2° as a function of azimuth in order to terrain-follow.

Two basic waveforms are used, one in the short-range interval, the other at long ranges. As shown in Figure 9-2, the short-range waveform consists of two, three, or four 20 μs pulses with identical Linearly Frequency Modulated (LFM) envelopes, contiguous in time but offset in carrier frequency for diversity. The pulse bandwidth is 400 kHz, so that the LFM Bandwidth Time (BT) product is 8 to 1. The long-range waveform consists of two, three, or four 160 μs, 200-kHz LFM pulses (BT = 32) which differ only in carrier frequency. They are also contiguous in time and offset in frequency for diversity gain. The number of pulses transmitted (i.e., one or two) varies with beam position. As shown in Table 9-1, a summary of the normal mode time schedule, four pulses are used at lower elevations where the maximum range is long, and two are used at upper elevations where the coverage is limited by the 100-kft altitude contour.

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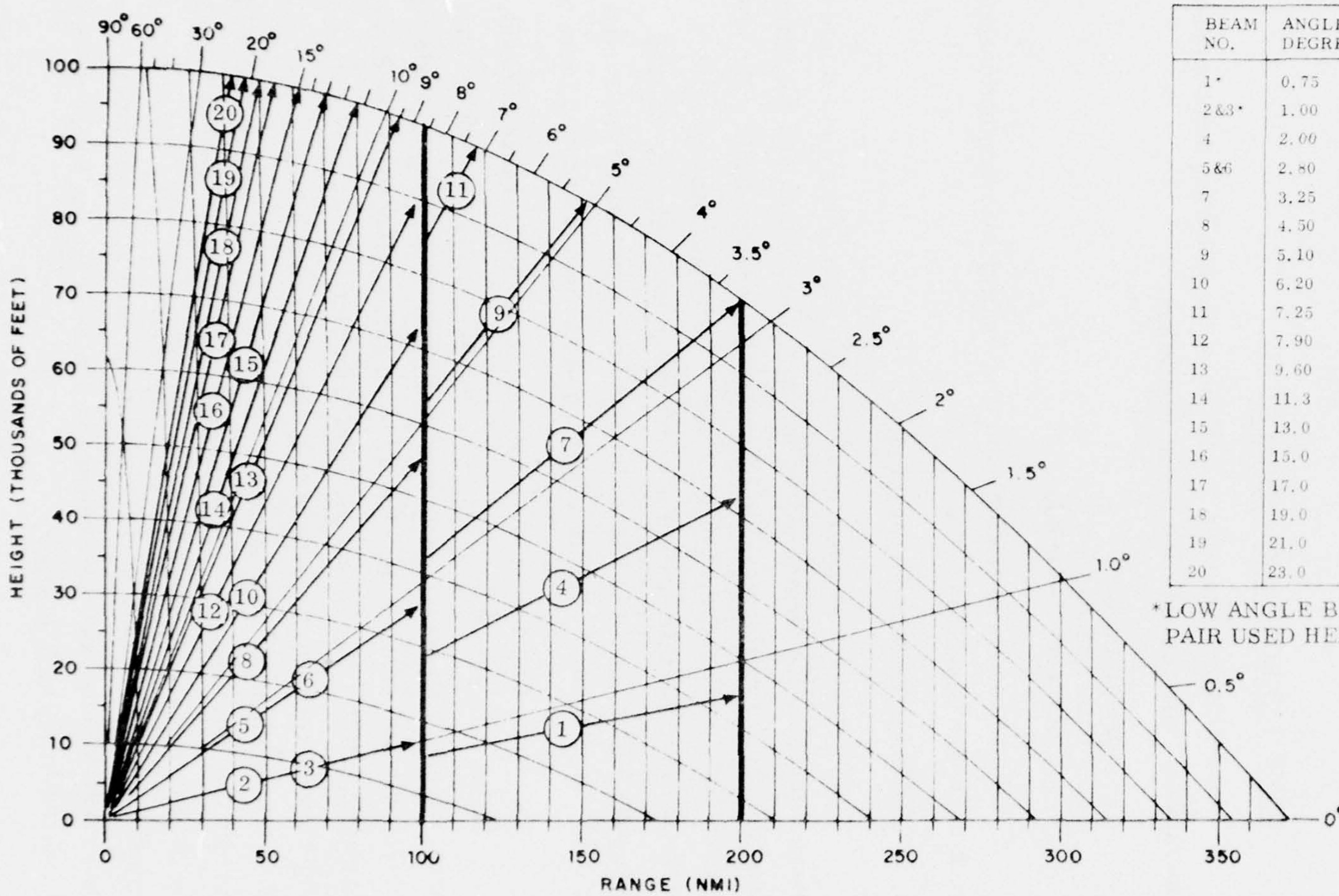
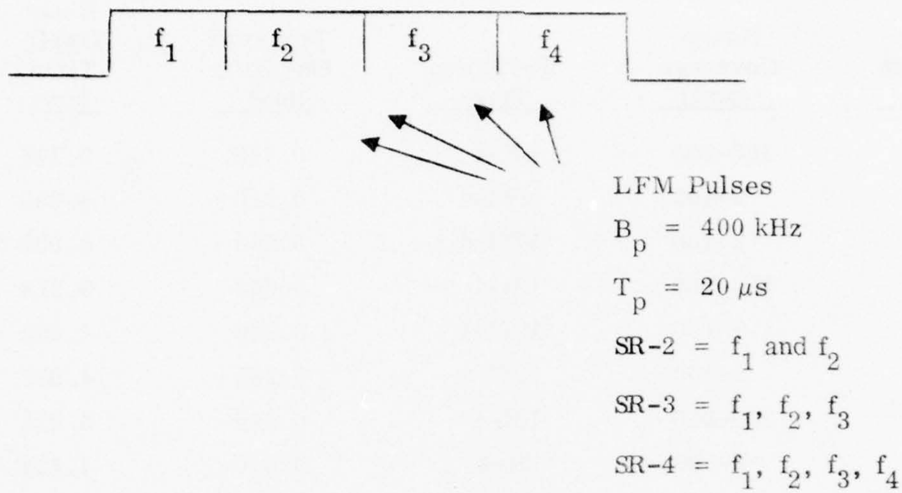


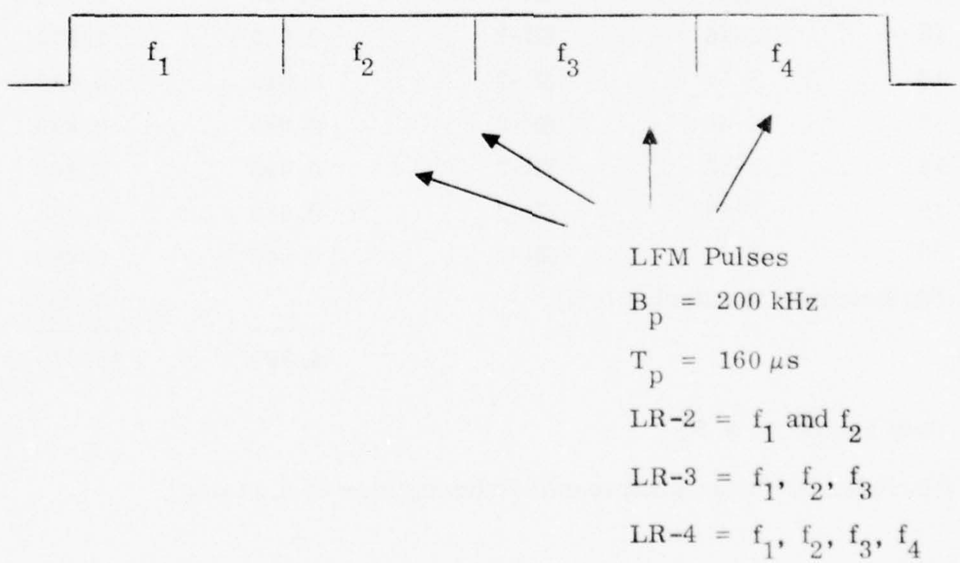
BEAM NO.	ANGLE DEGREES
1*	0.75
2&3*	1.00
4	2.00
5&6	2.80
7	3.25
8	4.50
9	5.10
10	6.20
11	7.25
12	7.90
13	9.60
14	11.3
15	13.0
16	15.0
17	17.0
18	19.0
19	21.0
20	23.0

*LOW ANGLE BEAM PAIR USED HERE

Figure 9-1. Normal Mode Elevation Scan Beam Schedule



a. Short-Range (SR) Waveform



b. Long-Range (LR) Waveform

Figure 9-2. Basic Waveforms with LFM Pulses

TABLE 9-1. NORMAL MODE ELEVATION SCAN TIME/ENERGY SCHEDULE

Beam No.	Range Coverage (nmi)	Waveform Type	Transmit On-Time (ms)	Beam Dwell Time* (ms)
1	100-200	LR-4	0.640	3.218
2	2-100	MTI-4	0.240	4.052
3	2-100	MTI-4	0.240	4.052
4	100-200	LR-4	0.640	3.218
5	2-100	MTI-4	0.240	4.052
6	2-100	MTI-4	0.240	4.052
7	100-200	LR-4	0.640	3.218
8	2-100	SR-4	0.080	1.424
9	100-175	LR-3	0.480	2.750
10	2-100	SR-4	0.080	1.424
11	100-135	LR-2	0.320	2.096
12	2-100	SR-4	0.080	1.424
13	2-100	SR-4	0.080	1.424
14	2-85	SR-3	0.060	1.219
15	2-75	SR-2	0.040	1.076
16	2-67	SR-2	0.040	0.980
17	2-60	SR-2	0.040	0.890
18	2-53	SR-2	0.040	0.800
19	2-47	SR-2	0.040	0.730
20	2-43	SR-2	0.040	0.680
Performance Monitoring (ms)			-	2.500
			4.300	45.279

Duty Factor = 9.5%

*Includes per beam pretransmit listening time of 0.11 ms.

In each of the two lowest beam positions of the short-range interval (beams 2, 3, 5, and 6 in Figure 9-1), the four-pulse short-range waveform is repeated three times for MTI processing, as required, to suppress either ground or sea clutter. The interpulse periods are staggered to eliminate blind speeds (to 2400 knots). Two different codes are used alternately. Stagger code 1 is used in beams 2 and 5 and stagger code 2 is used in beams 3 and 6. The two stagger codes have complementary MTI pass band responses. That is, at frequencies where one response is relatively low, the other is relatively high. This is indicated in Figures 9-3 and 9-4, which are plots of the frequency responses of the complementary three-pulse MTI waveforms and the composite response generated by taking the greater of the two at each frequency. Figure 9-3 indicates the response of the MTI with weights set to suppress the ground clutter, and Figure 9-4 indicates the response of the MTI with weights set to suppress sea clutter. These figures indicate that the composite response is less than -4 dB over only 4% of the frequency interval from 180 to 11,000 Hz (40 to 2500 knots), and the minimum pass band response throughout this interval is -6 dB.

b. WEATHER MODE

During normal operation, the environment is monitored on a beam-by-beam basis via a background level estimating circuit within the signal processor. A high level of range-extended interference in any beam position in the short-range interval will set a "clutter bit" in a status register within the General Purpose (GP) computer associated with that beam position. If clutter bits are set in at least two beams within the same or in adjacent azimuth cells, a weather condition is declared and the operator at the Operations Center is alerted via an illuminated indicator on the control panel.

The weather mode is automatically activated after the "weather present" declaration (although an override capability is available at the operations center). The normal search sequence is interrupted and a weather adaptation procedure is implemented. Either one or two sequences of MTI waveforms are transmitted and processed in each azimuth cell containing at least one beam with a set clutter bit. If any of the four lowest short-range beams (in which ground or sea clutter can be expected and three pulse MTI waveforms are normally transmitted) contains a set clutter bit, a sequence of five identical 6-pulse MTI waveforms, plus one normal 3-pulse MTI waveform, are transmitted through a beam broadened to span the 0 to 3° elevation sector. If any of the eight upper short-range beams (in which ground or sea clutter returns are not present) contains weather, a sequence of eleven identical 3-pulse MTI waveforms plus a single non-MTI short-range waveform are transmitted through a beam broadened to span the 3° to 20° interval.

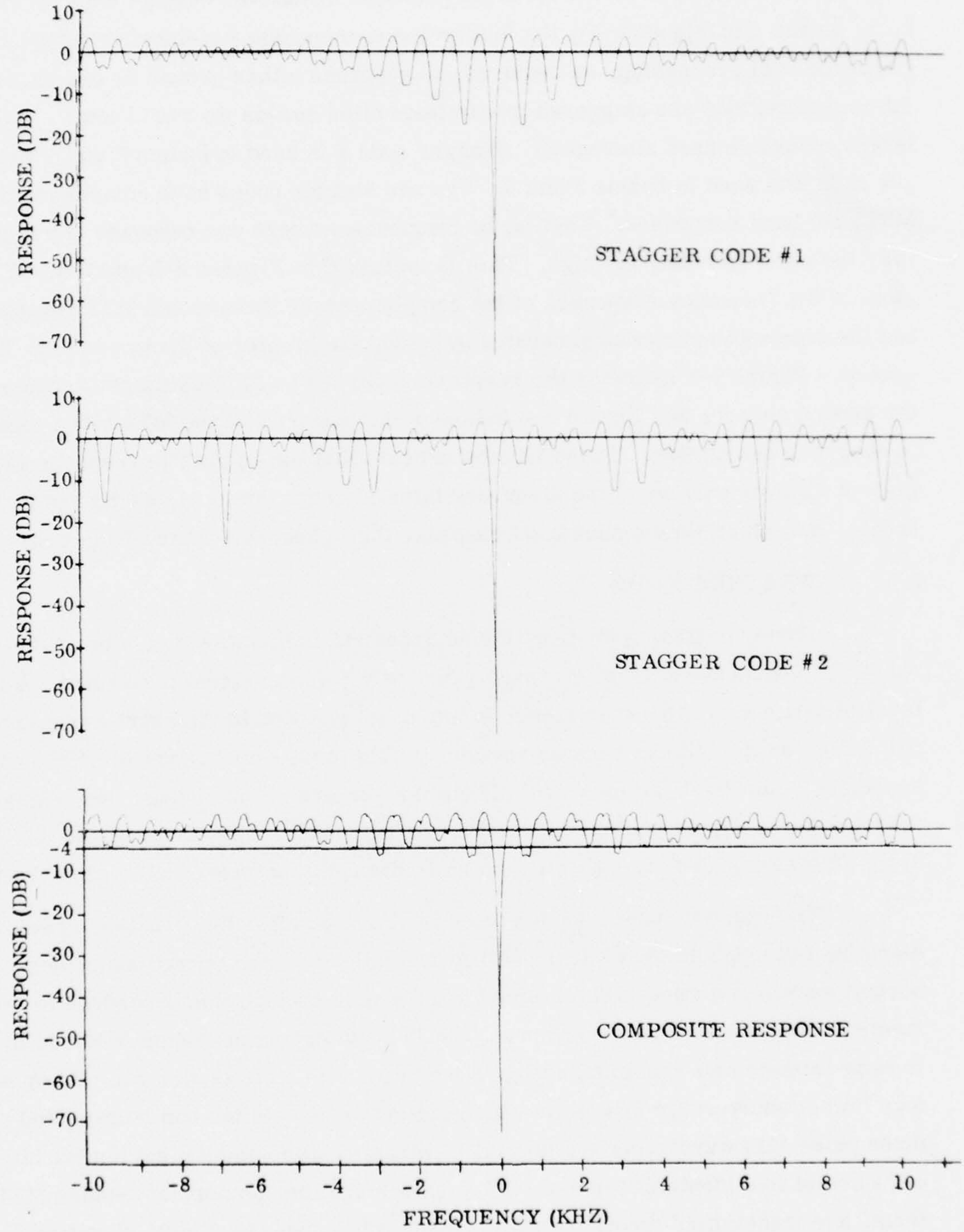


Figure 9-3. Normal Mode 3-Pulse MTI Response vs Ground Clutter

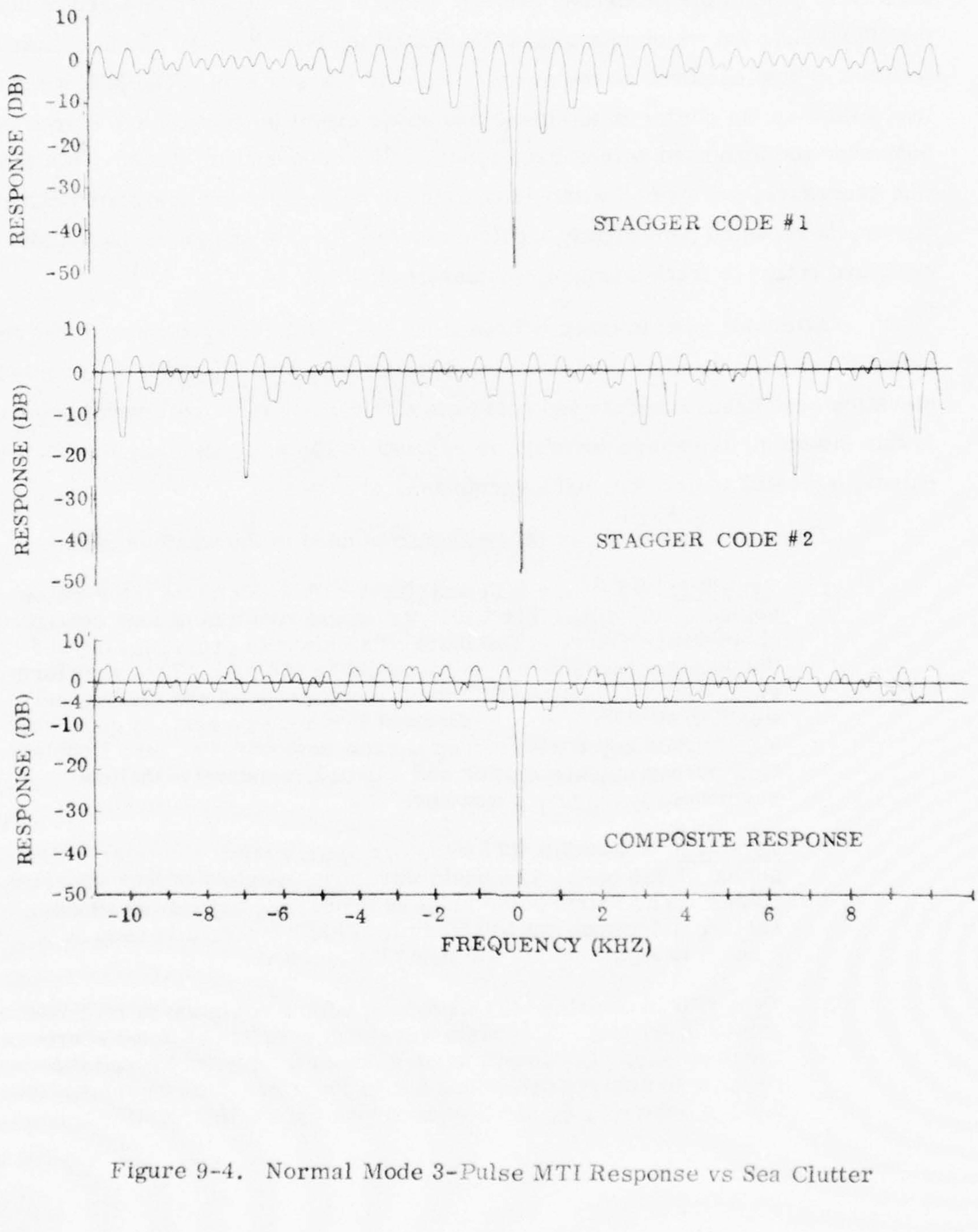


Figure 9-4. Normal Mode 3-Pulse MTI Response vs Sea Clutter

Each MTI waveform within a sequence is processed with a different set of MTI weights, with each set generating an MTI frequency response with a different clutter notch position. For example, the five 6-pulse MTI weight sets generate weather suppression notches centered at 0, ±50 Hz, and ±100 Hz. The clutter residues from each of the processed returns within a sequence are compared to determine the MTI weight set which minimizes the clutter (or equivalently, which clutter notch position is best centered on the mean Doppler of the weather). The MTI weight sets that minimize the clutter in the lower and upper elevation sectors are stored in the computer and then used within that azimuth cell on subsequent scans. This adaptation procedure, performed within each azimuth cell within the designated clutter sector, is repeated periodically (at five minute intervals or less as established by keyboard entry) to track changing weather conditions.

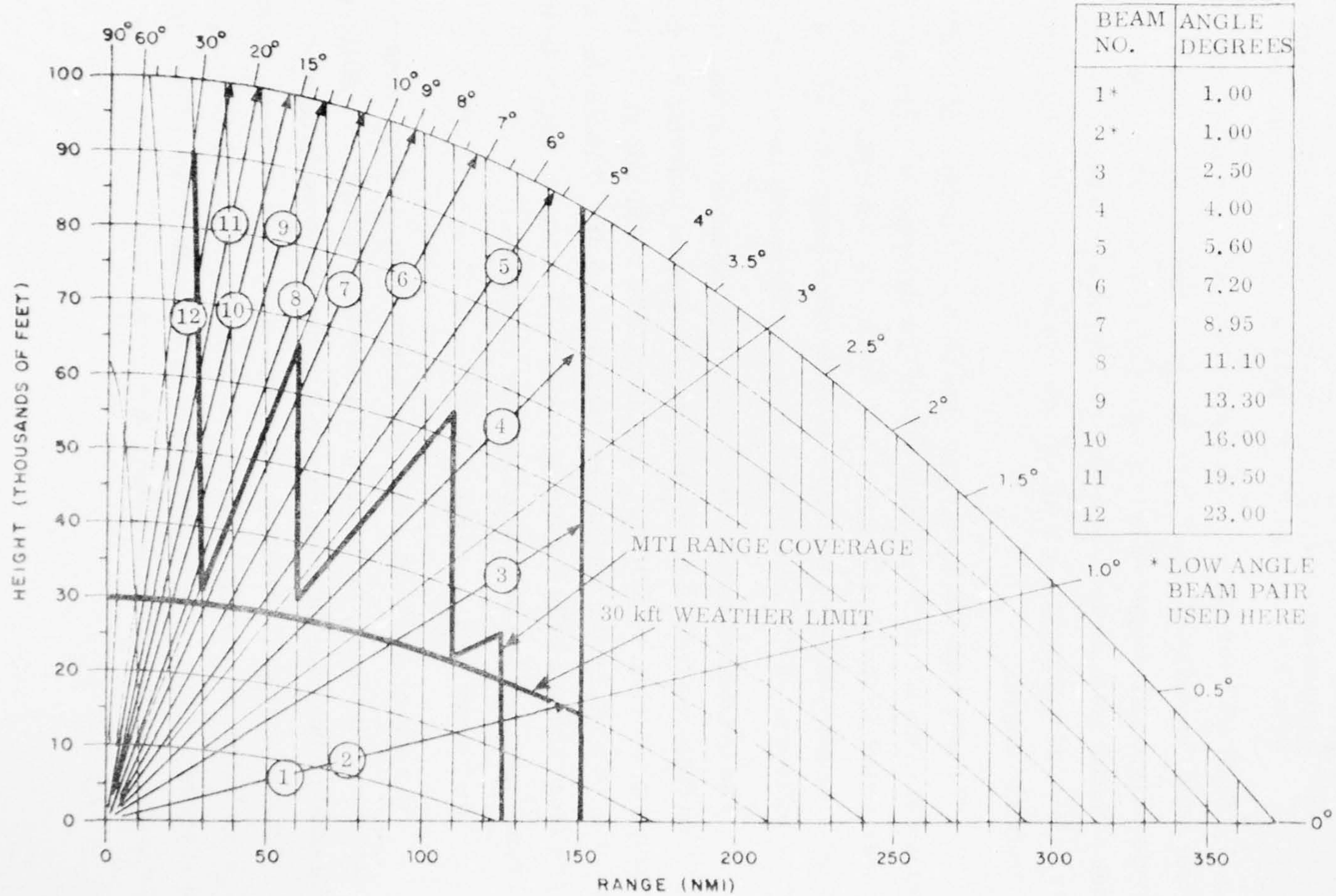
After one scan is taken to determine the "best" MTI weight sets for each azimuth cell, the weather mode search sequence follows. Figure 9-5 indicates the elevation scan beam schedule and coverage within an azimuth cell containing weather. In this situation, the range coverage is reduced to 150 nmi, and only the short-range pulses, repeated to generate MTI waveforms, are used.

There are four types of MTI waveforms used in the weather mode:

1. Type W1: A 6-pulse MTI waveform with a minimum inter-pulse period of 125 nmi. The basic waveform consists of four contiguous short-range pulses. The sixth pulse alone is processed beyond the weather to achieve detections out to 150 nmi. This waveform is used in beams 1 and 2 to suppress terrain or sea clutter and weather simultaneously. To meet this requirement, it generates a compound notch with a deep narrow component at zero Doppler to suppress surface clutter and a broad, relatively-shallow component to suppress weather.

2. Type W2: A 4-pulse MTI waveform with a minimum inter-pulse period of 110 nmi. The basic waveform consists of four short-range pulses. The fourth pulse alone is processed beyond the weather to achieve detections out to 150 nmi. This waveform is used in beams 3 and 4 to suppress the weather clutter.

3. Type W3: A 3-pulse MTI waveform with a minimum inter-pulse period of 60 nmi. The basic waveform consists of three short-range pulses. The fourth pulse alone is processed beyond the weather to achieve detections out to 150 nmi. This waveform is used in beams 5, 6, and 7 to suppress the weather clutter.



BEAM NO.	ANGLE DEGREES
1*	1.00
2*	1.00
3	2.50
4	4.00
5	5.60
6	7.20
7	8.95
8	11.10
9	13.30
10	16.00
11	19.50
12	23.00

* LOW ANGLE BEAM PAIR USED HERE

Figure 9-5. Weather Mode Elevation-Scan Beam Schedule

4. Type W4: A 3-pulse MTI waveform with a minimum inter-pulse period of 30 nmi. The basic waveform consists of two short-range pulses. The third pulse alone is processed beyond the weather to achieve detections to the coverage limit. This waveform is used in beams 8 through 12 to suppress the weather clutter.

Each MTI waveform type is transmitted on either of two different stagger codes, which provide complementary pass band responses. Associated with each MTI waveform type and stagger code is a series of MTI weight sets. Each weight set provides a clutter notch centered at a different doppler frequency. The particular weight sets to be used within any one azimuth cell are determined in the adaptation procedure as described above.

The composite frequency response (i.e., the greater of the SC1 and SC2 responses) of the W1 MTI waveform with MTI weights set to suppress ground and weather clutter is shown in Figure 9-6. This curve shows the composite response with MTI weights chosen to provide a weather notch centered at -100 Hz. The deep narrow component of the notch at zero Doppler suppresses the ground clutter.

The weather mode elevation scan energy schedule is summarized in Table 9-2. The time required to complete an elevation scan, including 2.5 ms for performance monitoring, is 59.0 ms. The associated round-trip gain loss at the crossover point between beams adjacent in azimuth is 3.5 dB. The weather mode is invoked only in those azimuth cells containing weather. The normal search template and 200-nmi range coverage are maintained at other azimuths.

c. EMERGENCY 2-D MODE

The operational modes described above cannot be implemented without the GP computer. However, in the event of a computer failure, surveillance can still be maintained by initiating an emergency 2-D mode via a console control. In this condition, the instructions for radar operation will come from read-only memories located within the hardware controllers which interface the radar with the computer. The real advantage of this mode is that it permits the maintenance of air surveillance while diagnostics are being performed on the computer.

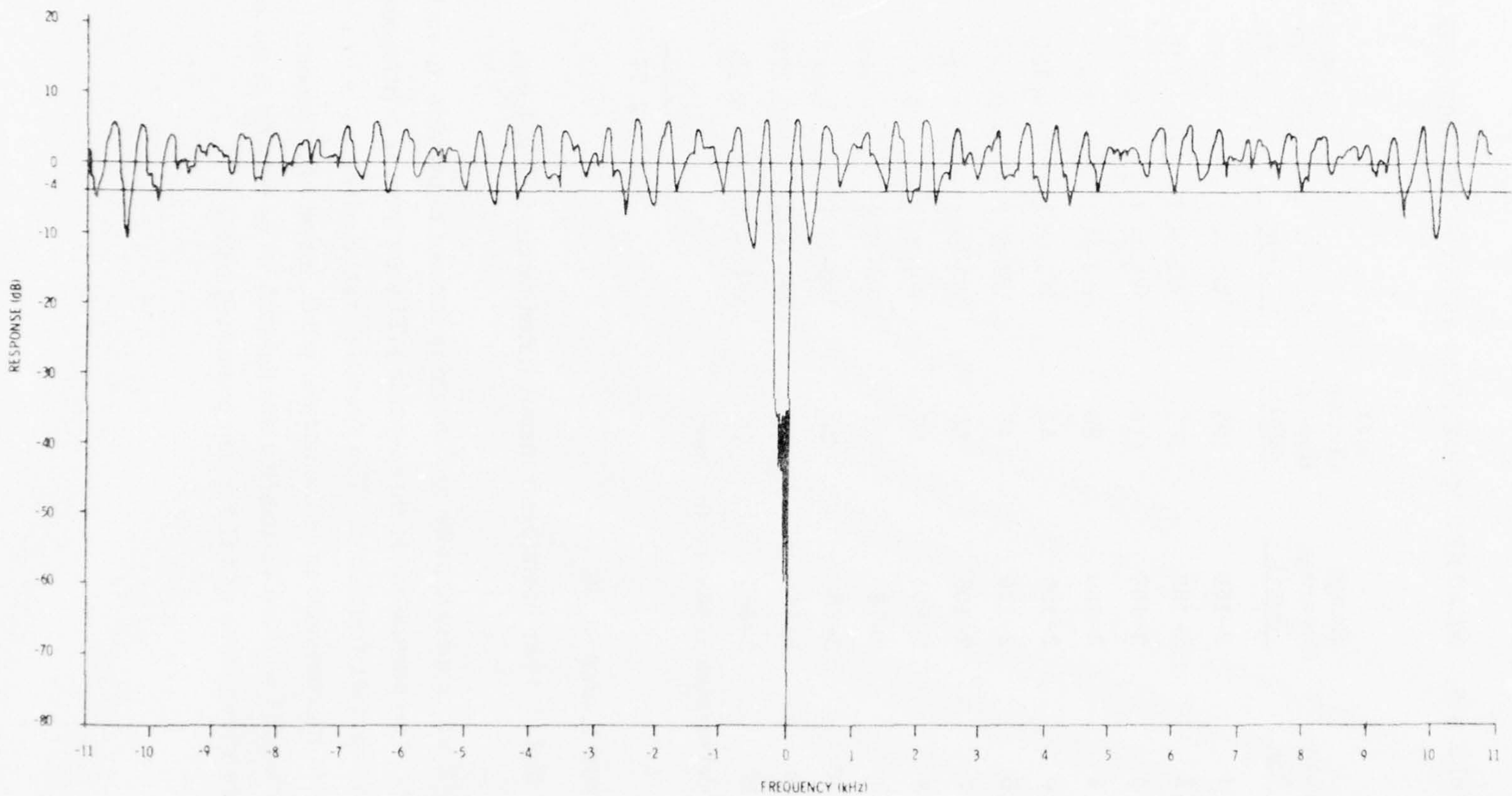


Figure 9-6. Weather Mode Six-Pulse MTI (W1) Composite Response

TABLE 9-2. WEATHER MODE ELEVATION SCAN TIME/ENERGY SCHEDULE

Beam No.	Range Coverage (nmi)	Max Clutter Range (nmi)	Waveform Type	Transmit On-Time (ms)	Beam* Dwell Time (ms)
1	2-150	125	W1-SC1	0.480	10.778
2	2-150	125	W1-SC2	0.480	10.991
3	2-150	110	W2-SC1	0.320	6.643
4	2-150	80	W2-SC2	0.320	6.868
5	2-150	60	W3-SC1	0.180	3.812
6	2-130	45	W3-SC2	0.180	3.790
7	2-108	35	W3-SC1	0.180	3.294
8	2-90	27	W4-SC1	0.120	2.271
9	2-75	23	W4-SC2	0.120	2.311
10	2-65	20	W4-SC1	0.120	1.963
11	2-55	18	W4-SC2	0.120	2.064
12	2-45	16	W4-SC1	0.120	1.716
Performance Monitoring (ms)				-	2.5
				2.74	59.001

Duty Factor = 5%

* Includes per beam pretransmit listening time of 0.1 ms.

A fixed, approximately $\csc^2$ beam is formed to provide elevation coverage from 0 to 20°. The normal mode three-pulse MTI waveform is continuously transmitted at a fixed carrier frequency. The resulting range coverage is to 100 nmi. The MTI waveform is processed as in the normal mode, except that automatic detection processing and position estimation are deleted. The outputs in the emergency 2-D mode are radar video and IFF video presented on the PPI.

2. POSITION ESTIMATION PROCESSING

a. HEIGHT AND AZIMUTH ESTIMATION

Determination of the azimuth and elevation of detected targets is made in the GP computer. The azimuth estimate is obtained by adding the array azimuth as determined from the Azimuth Change Pulse (ACP) count to the estimate of arrival angle relative to array azimuth as determined by monopulse processing. The elevation estimate is obtained by adding the monopulse derived angle to the beam boresight angle.

The array generates sum (Σ), azimuth - difference (ΔAz), and elevation - difference (ΔEl) beams. At the signal processor input, these are converted to Σ, $\Sigma + i\Delta Az$, and $\Sigma + i\Delta El$ signals. Since the transmit waveform consists of two to four pulses, offset in frequency, two to four diversity channels are processed for each of three beams.

When a target detection occurs, the in-phase and quadrature modulations of the signals (all frequencies on each of three beams) are sent to the GP computer. The delta-to-sum ratios, $\Delta Az/\Sigma$ and $\Delta El/\Sigma$, are then calculated at each frequency. There is a unique relationship between delta-to-sum ratio and target arrival angle. This transformation is made via look-up tables. The results are two estimates of azimuth and elevation, one at each frequency. Single estimates are derived by taking a weighted average of the individual frequency estimates (weighted according to the sum signal magnitude). Target height is then computed from the elevation and range estimates, after correcting the elevation angle for beam bending, accurately accounting for earth's curvature, and adding radar height to the relative height estimate.

b. LOW-ANGLE HEIGHT FINDING

At low elevation angles, when the antenna mainlobe is on the ground, conventional techniques, including monopulse processing, provide very inaccurate height estimates because of the presence of multipath. In the radar when the beam elevation is below 2°, the conventional monopulse technique is replaced by a special low-angle height-finding technique. It, too, is a monopulse technique, but in place of the sum, elevation-difference beam pair, it uses a pair of squinted sum beams. The lower sum beam, E_L, corresponds to the conventional sum or reference beam. The

upper beam, E_U, (squinted up by 1°) replaces the difference beam. As illustrated in Figure 9-7, the ratio of the beam outputs is uniquely related to arrival angle. The figure also indicates that with the low-angle beam pair, in contrast to conventional monopulse, multipath is restricted to the sidelobe region at target elevations down to 0.5° above the radar horizon. As such, the adverse effect of multipath on the height estimate accuracy is minimized.

At low elevation, the array outputs processed are the upper and lower sum beams and the azimuth-difference beam. They are processed identically to the conventional beam set, except that the look-up table in the computer which relates the beam ratios to arrival angle is different.

c. RANGE ESTIMATION

Target range is determined directly from the range time at which the magnitude of the processed signal, exceeding the detection threshold, reaches its peak value. In fact, the signal modulation components sent to the computer for the arrival angle determination are the values sampled at the instant the signal magnitude peaks.

3. PERFORMANCE MONITORING AND FAULT LOCATION

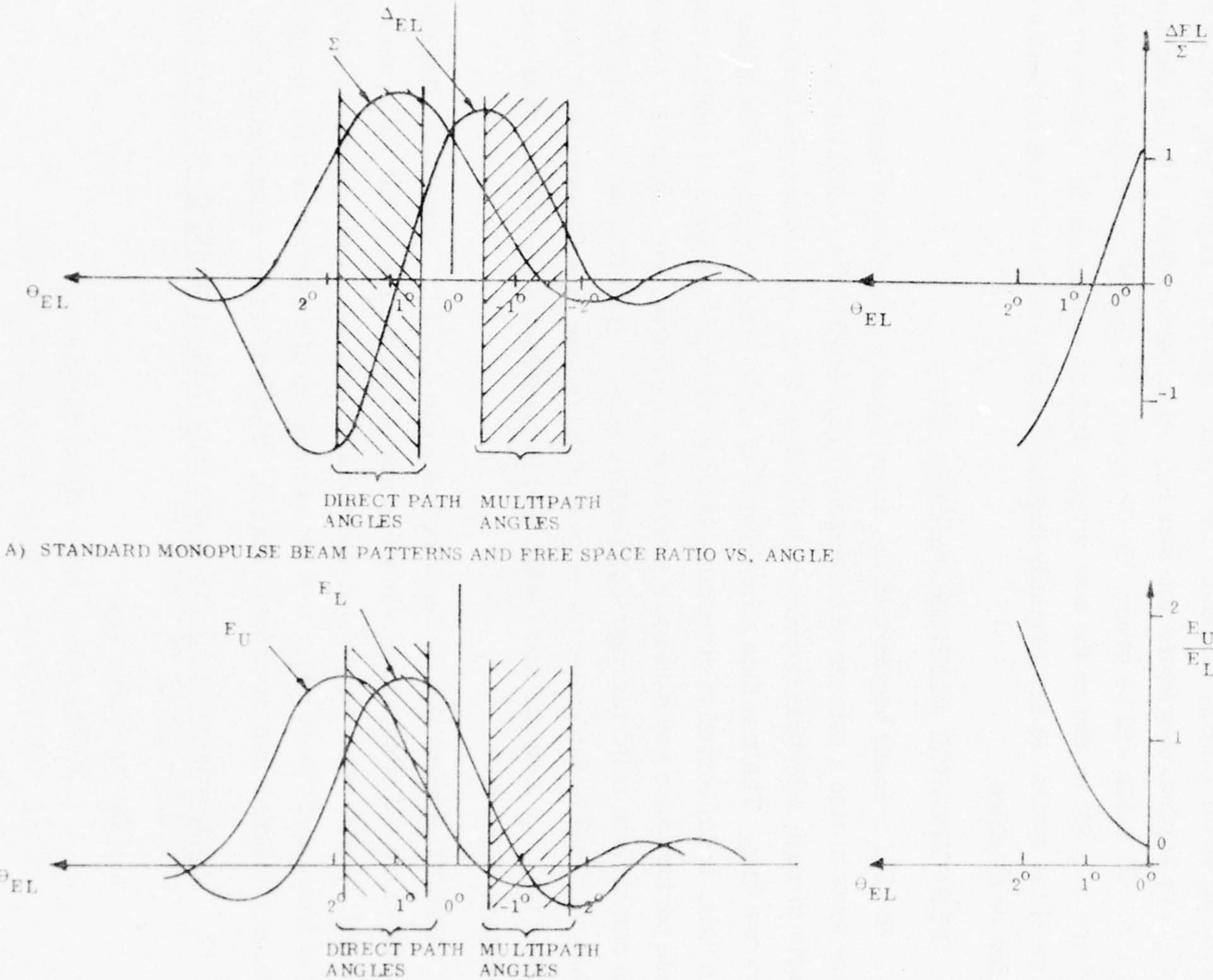
During normal operation, the radar will automatically and continuously test all aspects of its own performance. It will take an average of 2.5 ms out of each 45.3 ms elevation scan (a 6% duty factor) to execute performance monitoring tests.

Two types of performance data are used for this purpose:

1. Status messages transmitted to the computer in the event of a power supply failure, failure of continuously monitored functions within the data processor interface hardware, or absence of signal or oscillator outputs from the rf exciter.

2. Performance monitoring tests scheduled by the computer between operational pulse repetition periods.

The CRT terminal provides direct indication to the maintenance man of a system failure. Also, upon request, it will display the performance of the system and major subsystems in quantitative terms.



A) STANDARD MONOPULSE BEAM PATTERNS AND FREE SPACE RATIO VS. ANGLE

B) LOW-ELEVATION BEAM PATTERNS AND FREE SPACE RATIO VS. ANGLE

Figure 9-7. Comparison of Low-Angle Beams and Conventional Monopulse Beams

The performance state of the system as determined by the Performance Monitoring (PM) routine is displayed at the Operations Center by the Performance Monitoring Status Display (PMSD). The PMSD, shown in Figure 9-8, contains nine lights, five hardware-oriented and four related to performance. In the absence of a failure, all lights will be green. In the event of a failure, sufficient processing is performed in PM to change the appropriate light or lights to either yellow or red; yellow if the system is in a partially degraded condition, red if it is seriously degraded or disabled.

a. PERFORMANCE MONITOR PROCESS FLOW

The PM process begins with the execution of a full cycle of scheduled PM tests. These tests utilize a number of commands which control the generation and routing of signals through selected elements of the system to provide meaningful hardware response data. The raw data accumulated in these tests, together with status message data, is processed to generate a large number of measures of performance. These performance measures are compared to performance standards. When any such comparison indicates degraded performance, a fault flag is set. The flag pattern is then analyzed to determine the source of the failure in sufficient detail to properly activate the CRT terminal and PMSD, and to reconfigure the system so as to minimize the impact of the fault.

The PM process flow is described in some detail in Figure 9-9. Having properly initialized the PM process and cancelled any old fault flags, a full PM cycle is then executed. A PM cycle consists of seven major test sets, each related to a different unit of hardware. Each major test set is made up of a number of tests designed to monitor a different aspect of performance. These tests are enumerated below.

1. Synchronizer/Signal Processor Data Control (S/SPDC)-Array Control Unit (ACU) PM Tests (64 Tests)

1.1 Synchronizer Test

1.1.1 Synchronizer Output Signal Subtest

1.1.2 S/SPDC Reply, Range and Azimuth Subtest

1.1.3 S/SPDC Auto Status and Output Queue Subtest

1.2 Array Data Subtest

1.2.1 Array Data Subtest

1.2.2 Array Tilt/Temperature Subtest

1.2.3 ACU Auto Status Subtest

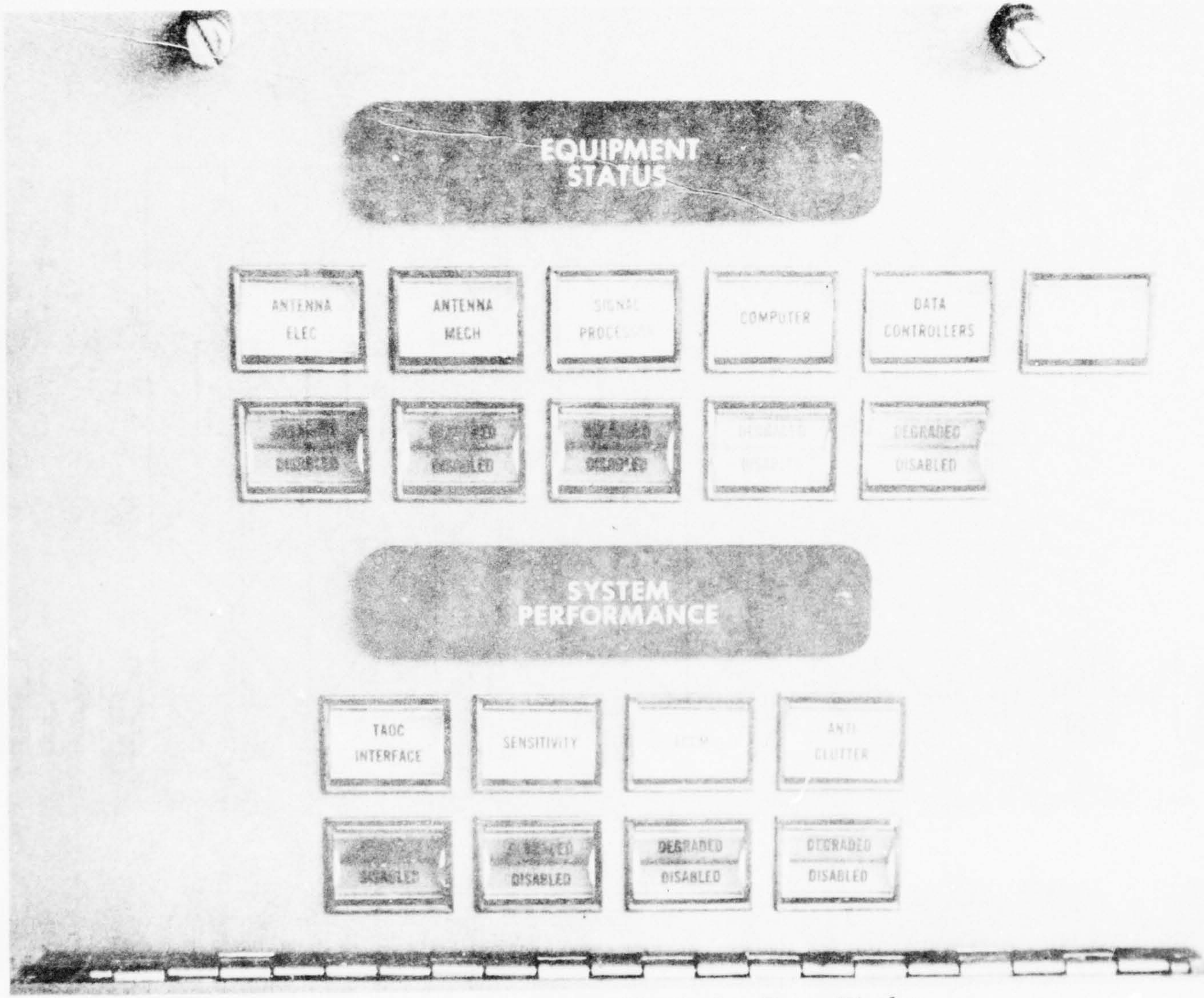


Figure 9-8. Performance Monitoring Status Display

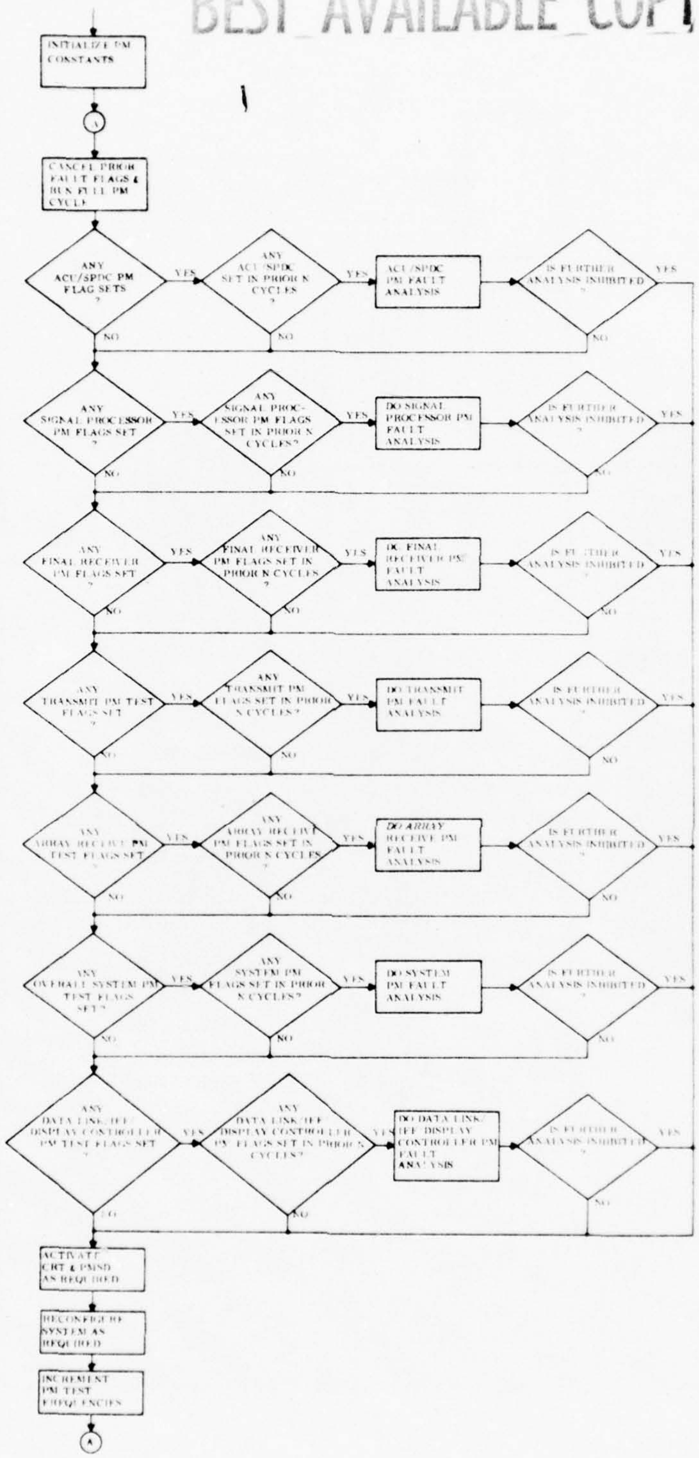


Figure 9-9. Performance Monitoring Process Flow

2. Signal Processor PM Tests (37 Tests)

   2.1 Long Range Processing Test

   2.2 Short Range/MTI Processing Test

3. Final Receiver PM Tests (129 Tests)

   3.1 Main Channel and STC Evaluation

   3.2 ECCM Evaluation

4. Transmitter PM Tests (180 Tests)

   4.1 Transmit Power Measurement

   4.2 Transmit Gain Evaluation

5. Array Receive PM Tests (52 Tests)

   5.1 Array Receive Signal Level Measurement

   5.2 Array Receive Noise Level Measurement

6. Overall System PM Tests (7 Tests)

   6.1 Clutter Suppression Test

   6.2 System Sensitivity Measurement

   6.3 Computer Self-Test

7. Data Link-Display-IFF Controller Tests (Status Messages Only)

   7.1 Data Link Controller Test

   7.2 Display Console Data Controller Test

   7.3 IFF Data Controller Test

Having run all 469 PM tests and accumulated the raw test data plus status message data the data associated with the S/SPDC-ACU Controller test is processed to generate S/SPDC-ACU Controller fault flags. If no such flags have been set, data from the second test set, the Signal Processor set is processed. If no flags are set, the next major test set is begun. In this manner, all major test sets are analyzed for fault flags in the sequence indicated by Figure 9-9.

After all seven major tests have been completed and no fault flags set, the RF exciter frequencies at which PM tests are run are changed. All allowable frequencies from among the set of 20 are used in PM. Incrementing the test frequencies completes a PM cycle. As indicated by Figure 9-9, it is then begun again.

When a fault flag is found in the data analysis of a major test set, the procedure changes course. A fault flag indicates a possible fault. To prevent the PM process from excessive false alarms, a fault flag must be set in the same major test set at least twice within N successive PM cycles (the same fault flag pattern is not required, however). The parameter N determines the intermittent fault frequency which will be identified as a fault. Its value shall be controllable through CRT keyboard entry.

When, within a major test set, a fault flag is set for at least the second time within N successive cycles, a confirmed fault condition is assumed. Then, a fault flag analysis associated with that major test set is performed. This analysis is essentially a pattern recognition procedure wherein particular sets of fault flags are interpreted as specific performance and/or hardware faults.

In performing the fault flag analysis, certain fault conditions result in a decision to inhibit further test analysis. Others permit continued testing.

Based upon results of the fault flag analysis, the CRT and PMSD are activated and, if required, the system is reconfigured. In the event of a confirmed fault with an unrecognizable fault pattern, a statement to that effect, together with an identification of the set fault flags, shall be displayed on the CRT.

b. QUANTITATIVE PERFORMANCE DATA

Quantitative performance data will be output on the CRT upon request via the associated keyboard.

The quantitative data relates either to computer program performance or hardware performance. A list of the data available is given below.

(1) Computer Performance Data

1. No. of targets reports available to Operations Center/scan
2. No. of targets in radar storage update queue/scan
3. No. of IFF targets processed/scan
4. No. of radar targets input/scan
5. No. of slots in single scan store released/scan
6. No. of azimuth cells adapted to clutter
7. No. of targets not reported to Operations Center/scan

(2) Hardware Performance Data

1. Signal Processor gain in long-range
2. Signal Processor gain in short-range (non-MTI) with simple pulse
3. Signal Processor gain in short-range (non-MTI) with LFM pulse
4. Signal Processor gain in short-range (MTI) with simple pulse
5. Signal Processor gain in short-range (MTI) with LFM pulse
6. Azimuth estimate bias error with full STC
7. Azimuth estimate bias error without STC
8. Elevation estimate bias error with full STC
9. Elevation estimate bias error without STC
10. Sum, elevation-difference, azimuth-difference, and SLB cancellation ratios achieved with ECCM processing
11. Transmitter output power at 4 test frequencies equally spaced across the 185 MHz operating band, and the test frequency values
12. Individual row transmitter outputs at each of the four test frequencies
13. Estimates of the transmit gain loss at each of the four test frequencies
14. Estimates of the receive sum and azimuth-difference channel SNR gains at each of the four test frequencies
15. Overall sum and azimuth-difference channel sensitivities at each of the four test frequencies
16. Array tilt and temperature

The data output on the CRT shall be in the format shown in Figure 9-10. It includes measured radar data and associated performance limits. Any data exceeding the indicated limit implies performance degradation. Request of this output shall be through the teletype CRT keyboard, using a simple command sequence.

PROCESSOR RESPONSE					
LR - LFM	(X X X X MIN.)	X X X X			
SR - SP	(X X X X MIN.)	X X X X			
SR - LFM	(X X X X MIN.)	X X X X			
MTI - SP	(X X X X MIN.)	X X X X			
MTI - LFM	(X X X X MIN.)	X X X X			
FINAL RECEIVER PERFORMANCE					
MONOPULSE ERROR					
AZ - STC 3	(X X X X MAX.)	X X X X			
AZ - STC 6	(X X X X MAX.)	X X X X			
EL - STC 3	(X X X X MAX.)	X X X X			
EL - STC 6	(X X X X MAX.)	X X X X			
CANCELLATION RATIOS					
SUM CHAN	(X X X X MAX.)	X X X X			
AZ CHAN	(X X X X MAX.)	X X X X			
EL CHAN	(X X X X MAX.)	X X X X			
SLB CHAN	(X X X X MAX.)	X X X X			
SYSTEM PERFORMANCE					
TEST FREQUENCY CHAN		X X	X X	X X	X X
XMIT POWER					
POWER	(X X X X MIN.)	X X X X	X X X X	X X X X	X X X X
XMIT GAIN LOSS					
GALO	(X X X X MAX.)	X X X X	X X X X	X X X X	X X X X
NOISE OUT					
SUM	(X X X X MAX.)	X X X X	X X X X	X X X X	X X X X
AZ	(X X X X MAX.)	X X X X	X X X X	X X X X	X X X X
SIGNAL OUT					
SUM	(X X X X MIN.)	X X X X	X X X X	X X X X	X X X X
AZ	(X X X X MIN.)	X X X X	X X X X	X X X X	X X X X
SENSITIVITY					
SUM	(X X X X MIN.)	X X X X	X X X X	X X X X	X X X X
AZ	(X X X X MIN.)	X X X X	X X X X	X X X X	X X X X
COMPUTER PERFORMANCE (PER SCAN)					
RADAR TGTS		X X X			
IFF TARGETS		X X X			
TAOC RPTS		X X X			
TAOC NO-RPTS		X X X			
RADAR QUEUE		X X X			
AVAIL STORE		X X X			
RELEASE STORE		X X X			
CLUT SECT		X X X			

Figure 9-10. Quantitative Data Output Sheet

c. FAULT LOCATION

Having determined, with the assistance of the performance monitoring procedure, that the system has failed, the maintenance man will cause the fault location program to be read into the computer from magnetic tape. The fault location procedure is very similar to Performance Monitoring. The computer commands a series of tests, first of the interface hardware, then of the signal processor, and so on in loops of increasing size. These tests differ from those run in Performance Monitoring in that special fault location hardware, primarily in the form of comparators, are used to assist the process.

The result of the automatic Fault Location process is the determination of the equipment area in which one fault lies. This "fault area" is an average of two analog boards, or 15 digital boards, or a particular row transmitter, receiver or power supply. This information, in the form of a fault area number, is output on the CRT. A maintenance manual is then used to relate fault area number to a particular board or row in the array.

The final phase of the fault repair process is semi-automatic. In the case of a board failure, it involves removing the board or boards from within the fault area, replacing them with good boards, and re-running the Fault Location program to verify that the fault has disappeared. The removed boards are then checked in a programmable board tester which is supplied as part of the system. This tester will generally indicate not only the particular board which has faulted, but also the bad integrated circuit.

SECTION X

150 NMI RANGE CONFIGURATION

The reduction in range from 200 nmi to 150 nmi results in reduced power aperture requirements of about 5 dB to detect targets with a 90% probability of detection, a 10^{-6} probability of false alarm, at the reduced range. Reduction of the power-aperture product is implemented by reducing power, while leaving aperture the same for both cases. As the horizontal dimension of the array is related to azimuth pattern loss, resolution, and scan rates it is essentially fixed. The vertical dimension in like fashion is related to the elevation pattern loss, and the elevation beam-width required for accurate height measurement, and is also essentially a constant. Therefore, the aperture size may be treated as a constant, leaving only power as a variable.

The reduced power requirement may best be obtained by reducing pulse length, leaving peak power the same. This will be accomplished by reducing the maximum number of frequency diversity pulses in any transmission from four to two. The loss to the system, will be a reduction of 4.33 dB due to diversity gain, as the signal-to-noise required for a 90% P_D with a $P_{FA} = 10^{-6}$ using 2 diversity channels is 14.84 dB, while for four channels it is only 10.51 dB.

Reducing diversity channels will reduce the number of receivers and signal processing channels by two. This will reduce the cost of a production system by 15 to 20%. As the basic system design will not be changed significantly, the nonrecurring costs will not be greatly effected.

Using the short range waveform with only two diversity channels presents a problem in obtaining the signal-to-noise ratio required for meeting the height accuracy requirements. This may be overcome by doubling the pulse length to 40 μs, so that the 150 nmi short range pulse with two diversity channels will be equal in time to the 200 nmi short range pulse with 4 diversity channels. Although this will leave still a net loss of about 1 dB, there will be sufficient signal/noise available to meet the accuracy requirement. Doubling the short waveform pulse length will increase the minimum range of the radar from 2 to 4 nmi.

The operational parameters, radar characteristics, basic method of operation, and basic equipment design all remain the same for both cases. The only major change in the system is in the equipment reduction in the receiver and signal processor.

SECTION XI

HARDWARE DESCRIPTION

1. MECHANICAL DESIGN

The 23.2 ft wide by 24.2 ft high antenna with IFF trough antenna can be housed in a standard 55-ft diameter, 39 ft high rigid or air-supported radome. If a new radome is required, the improved CW-860 metal space-frame radome is favored because of its proven all-around performance. Reliable operation in high wind loading and icing environments and long, maintenance-free life are definite attributes for remote and/or unattended operation. The random geometry of the CW-860 and the thin aluminum frame members minimize sidelobe distortion as well as overall bore-sight shift of the main beam. Signal attenuation through the CW-860 radome for the L-Band antenna system is approximately 0.5 dB with beam pointing disturbance less than 0.1 mrad.

The signal and data processing equipment can be housed in existing facilities or in a modular building positioned under the antenna tower, as shown in Figure 11-1. The building layout shown in Figure 11-2 provides a functional equipment arrangement, as well as equipment maintenance and personnel support facilities. An important feature of the design is the relatively modest facility required to house the nonradome equipment. This is, of course, the result of the distributed, solid-state array electronics.

2. ANTENNA GROUP

Figure 11-3 is a block diagram describing the array operation. The array aperture is formed by 44 horizontal linear arrays, or row feed networks, stacked vertically. These row networks are stripline corporate feeds which generate sum and azimuth-difference beams. They also contain monitoring couplers used either to sample the transmit signal or to inject signals into the receive paths in order to automatically and remotely monitor performance, locate faults, and align the array.

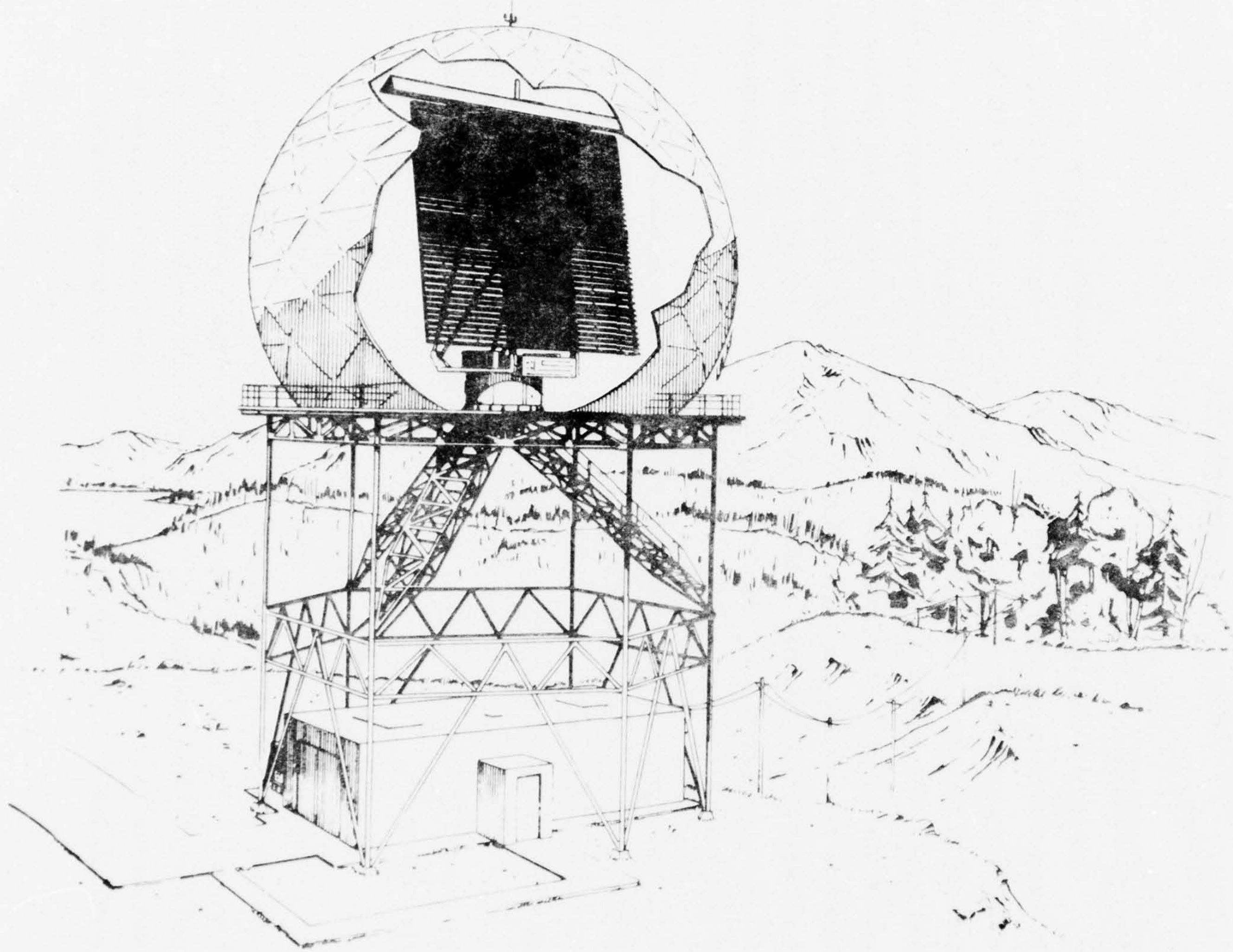


Figure 11-1. Radar in New Facility

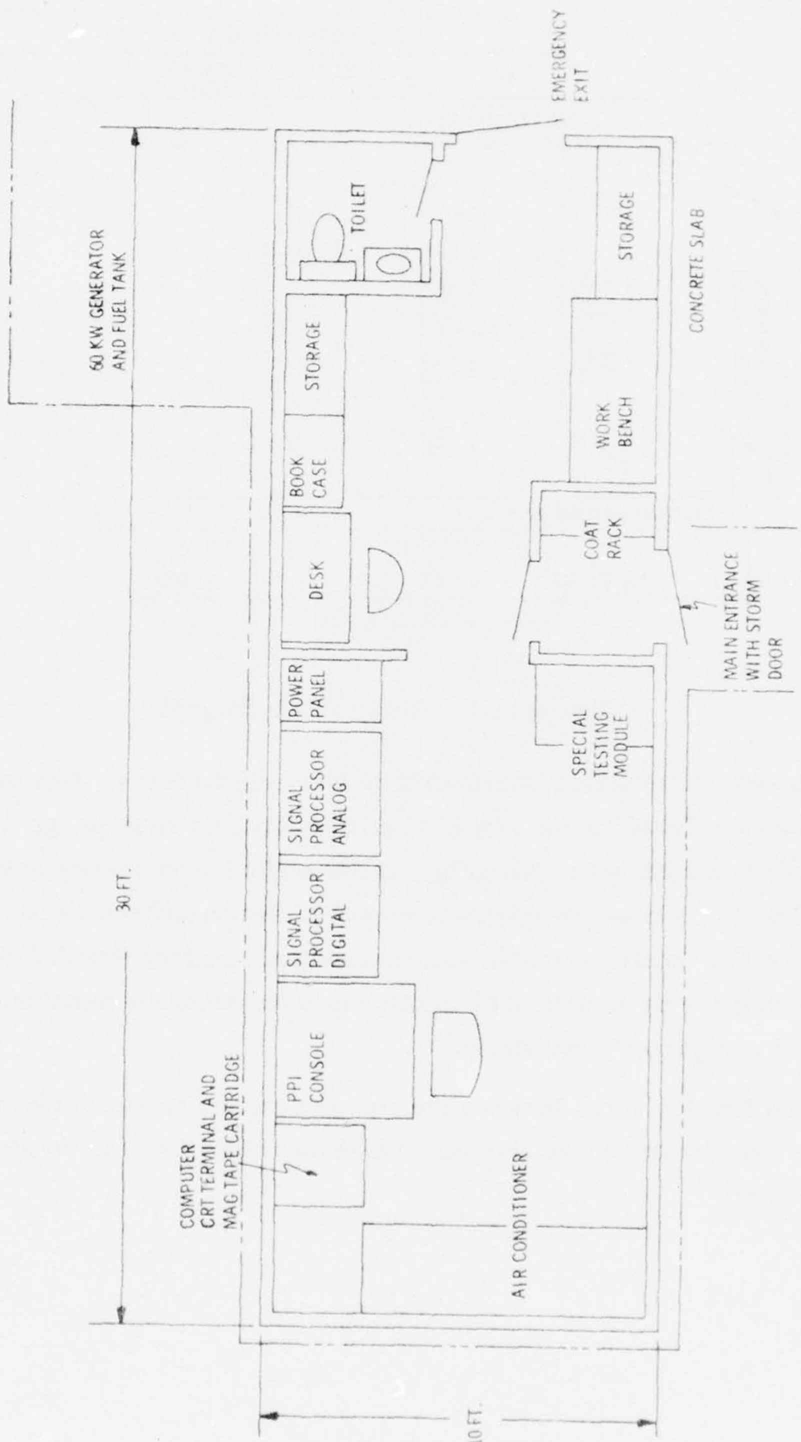


Figure 11-2. Building Layout

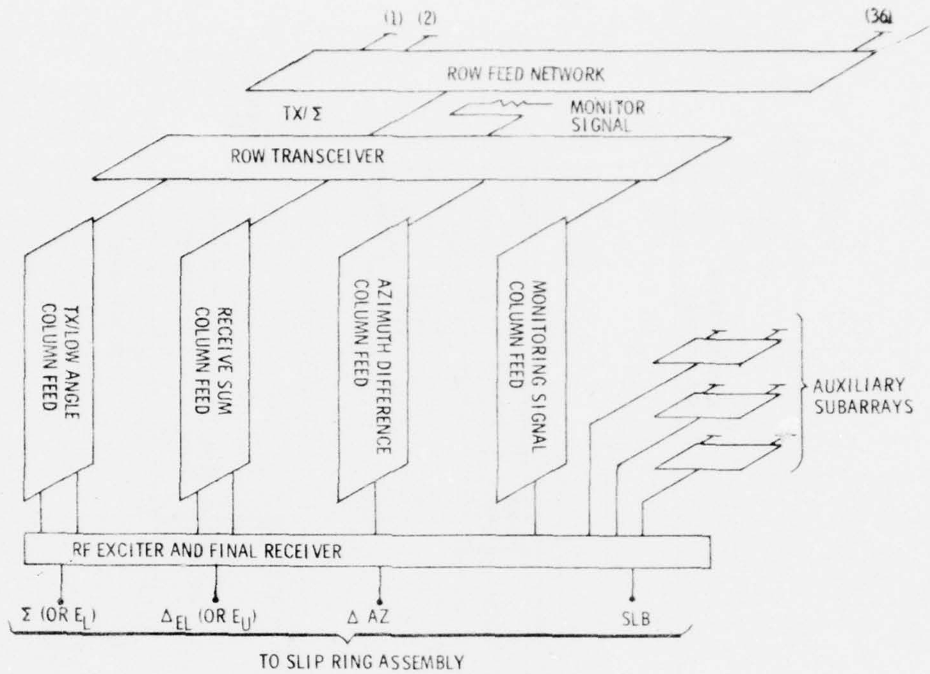


Figure 11-3. Array Block Diagram

Row-to-row distribution is provided by four column feeds. One feedline provides low level RF drive for the row transmitters and, on receive, generates the pair of squinted sum beams required by the low-angle height finding technique. A second feedline collimates the receive sum and elevation-difference beams. The third feedline forms the receive azimuth-difference signal, and the fourth feedline distributes and collects monitoring signals used in automatic performance monitoring, fault location, and array alignment procedures.

The row transceivers, between the row and column feeds, perform the functions of RF power generation, phase shifting, duplexing, filtering, and receiver preamplification.

Since the aperture amplitude taper is the product of the row and column feed taper, the far-field radiation patterns exhibit a corresponding product characteristic. Thus, all sidelobes off the azimuth and elevation principal planes are suppressed below -50 dB. Low sidelobes in the elevation principal-plane are achieved through a self-calibration procedure that compensates for component phase drifts. The azimuth principal-plane pattern achieves low sidelobes without monitoring, since the beam-forming network contains only passive components.

Three auxiliary subarrays are mounted around the periphery of the main antenna. They provide signals for sidelobe blanking (and other ECCM processing if required).

The RF exciter, mounted on the rotating platform, converts the 75-MHz transmit signal modulation, received from the waveform generator through the slip ring assembly, to a low-level array drive signal at the appropriate agile L-Band frequency.

The final receiver, also mounted on the rotating platform, down-converts the column feed and sidelobe blanker subarray outputs to 75 MHz for transmission, via the slip ring assembly, to the shelter electronics. According to the state of input switches (set on a pulse-to-pulse basis by the computer), the final receiver will accept from the column feeds either the pair of squinted sum beam signals or the sum and elevation-difference beam signals. The azimuth-difference signal and sidelobe blanker signals are always taken. The final receiver also contains input switching which permits any one of the three primary signals (i.e., azimuth-difference and sum/elevation-difference or squinted sum beam pair) to be routed through the sidelobe blanker channel in the event of a hardware fault.

The 44 antenna row feeds and transceivers, the latter packaged in groups of four, are housed in an aluminum backup structure, as shown in Figure 11-4. The center section of the array presents a solid surface of electronic enclosures. The outer or wing sections of the array provide minimum air flow blockage due to the openness of the row feed and septum assemblies. Such openness of the array minimizes drive power requirements as well as wind loading on an exposed or nonradome housed system.

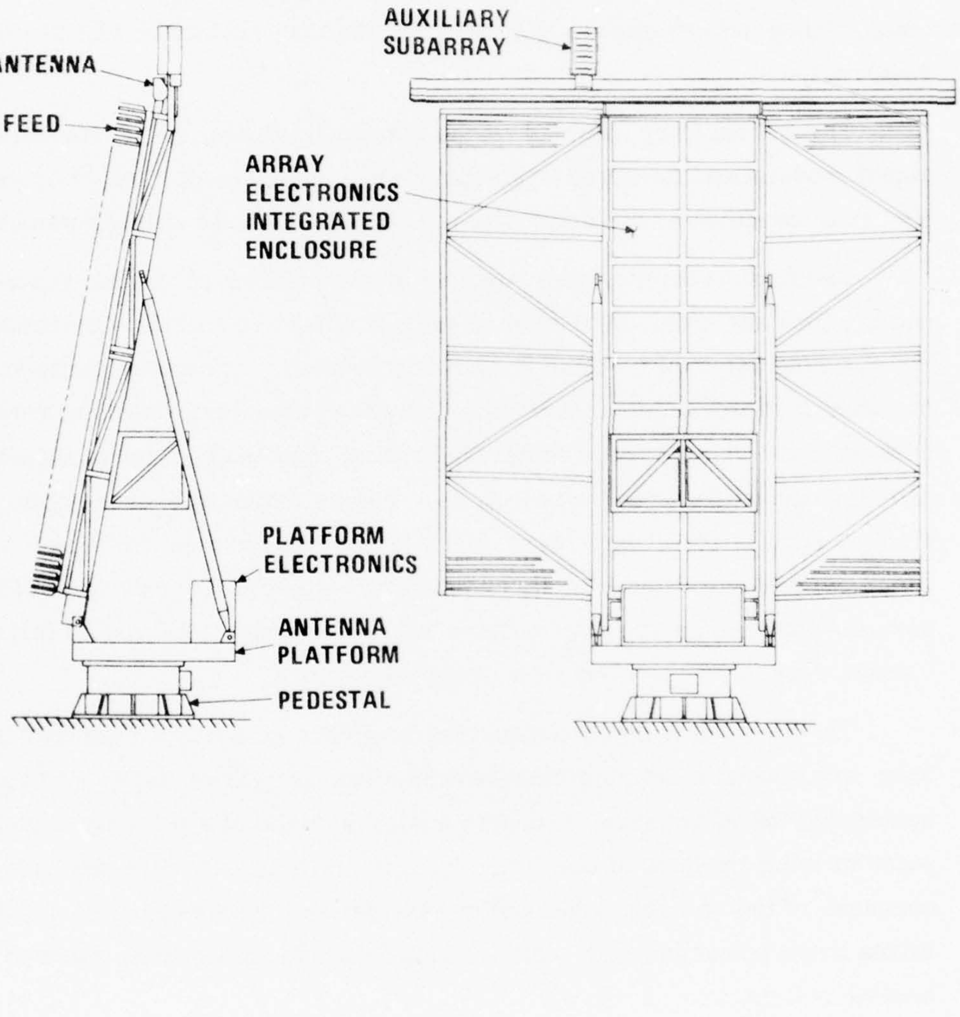


Figure 11-4. Array Backup Structure

The antenna array is mounted on an azimuth platform and support pedestal, as shown in Figure 11-5. The platform accommodates array front and back stay supports as well as final receiver, exciter, and power supply enclosure. Since the main array receivers are above the azimuth axis, slip rings can handle the signal flow to the off-array processor. The rotary joint accommodates the microwave IFF signal path. The pedestal housing supports the rolling element bearing and azimuth drive system.

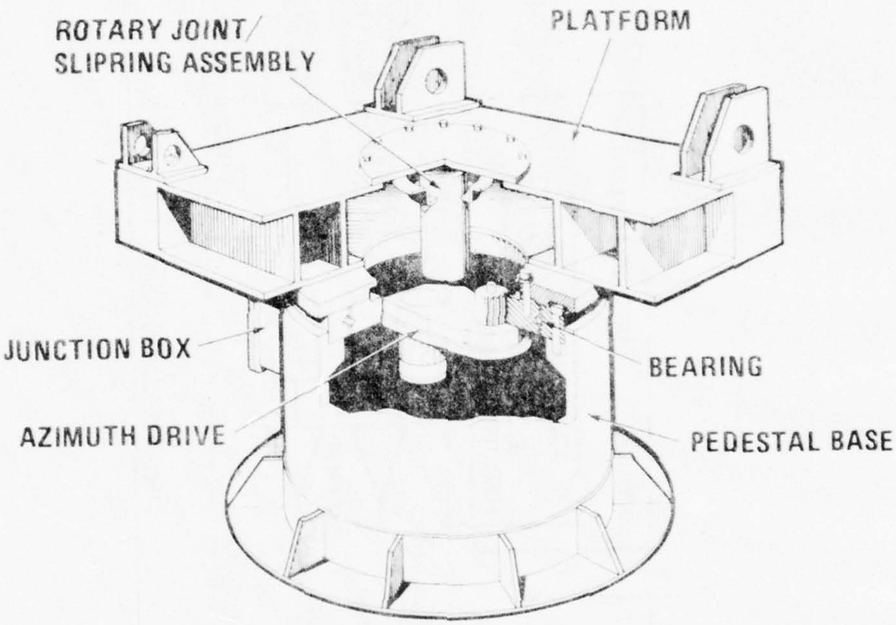


Figure 11-5. Platform and Support Pedestal

a. ROW TRANSCEIVERS

The row transceivers provide amplification, duplexing, filtering, and phase shifting of transmit and receive signals. As indicated in the block diagram, Figure 11-6, the RF drive from the transmit column feed is fed through a four-bit pin-diode phase shifter to a driver amplifier which drives the output amplifiers. The combined power delivered to the circulator in each row is on the average 830 W. The output amplifiers or power modules, containing one driver transistor and two paralleled output transistors, put out approximately 100 W of peak power at duty cycles up to 15%. At this power level the peak junction temperature of the output transistor is

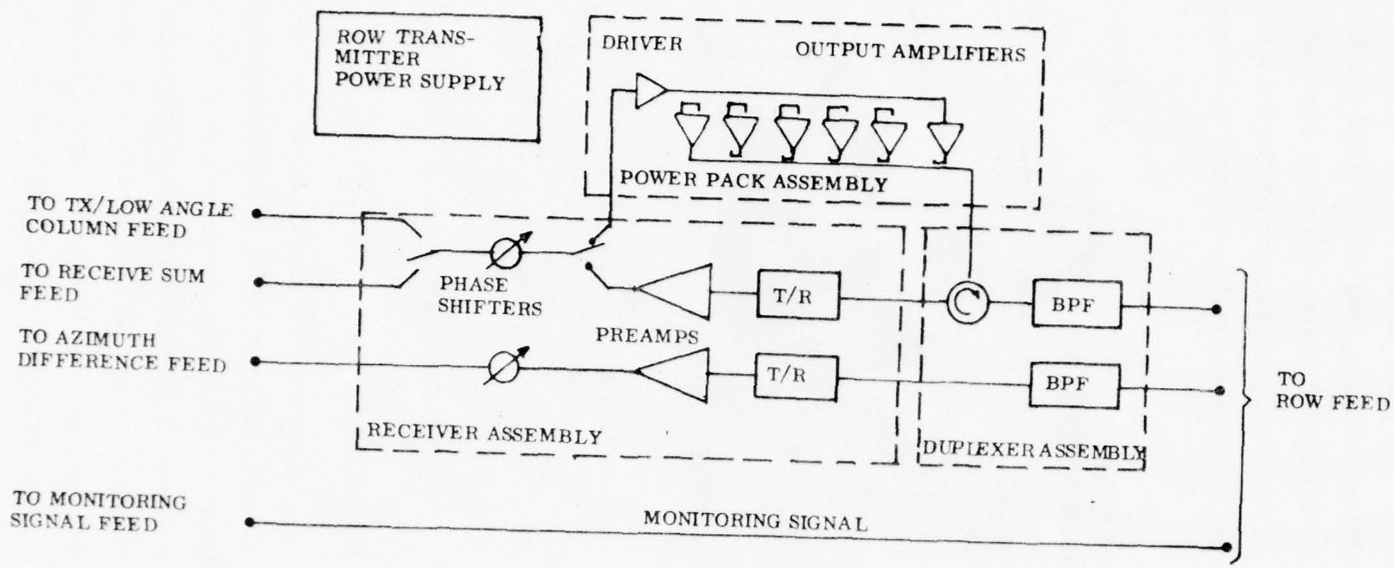


Figure 11-6. Row Receiver Block Diagram

limited to 125°C with a baseplate temperature of 52°C. Packaged with the row transmitter output amplifiers is approximately 0.1 farads of capacitance to provide dc energy storage. With this storage, the row transmitter power supplies are required to provide only recharge current rather than peak dc current.

The two receiving paths in a row transceiver (sum and azimuth-difference) include logic-gated Transmit/Receive (T/R) switch-limiters which provide overload protection for the low-noise preamplifiers during transmit and receive states. The preamp is a two-stage, balanced amplifier with a noise figure of 2.3 dB and a gain of 23 dB.

The row transceiver packaging is a modification of that used on the AN/TPS-59. It permits close proximity between the active electronics and the radiating elements, and a physical configuration which is easily maintained. The replaceable subassemblies are small, the heaviest weighing 25 lbs. Using the monitoring couplers within the row feeds and the switching control within the row transceivers, fault location tests may be executed and a maintenance man will know in advance which parts to take to the array and the particular subassemblies to be replaced.

3. PROCESSING CENTER

The Processing Center consists of the signal processor, data processing subsystem, and maintenance console.

a. SIGNAL PROCESSING SUBSYSTEM

The signal processing subsystem is comprised of a preprocessor, a waveform generator, and a digital signal processor. The first two, primarily analog equipment, are housed together in one cabinet, and the digital signal processor is in a second two-bay cabinet. A first level block diagram of this equipment is shown in Figure 11-7.

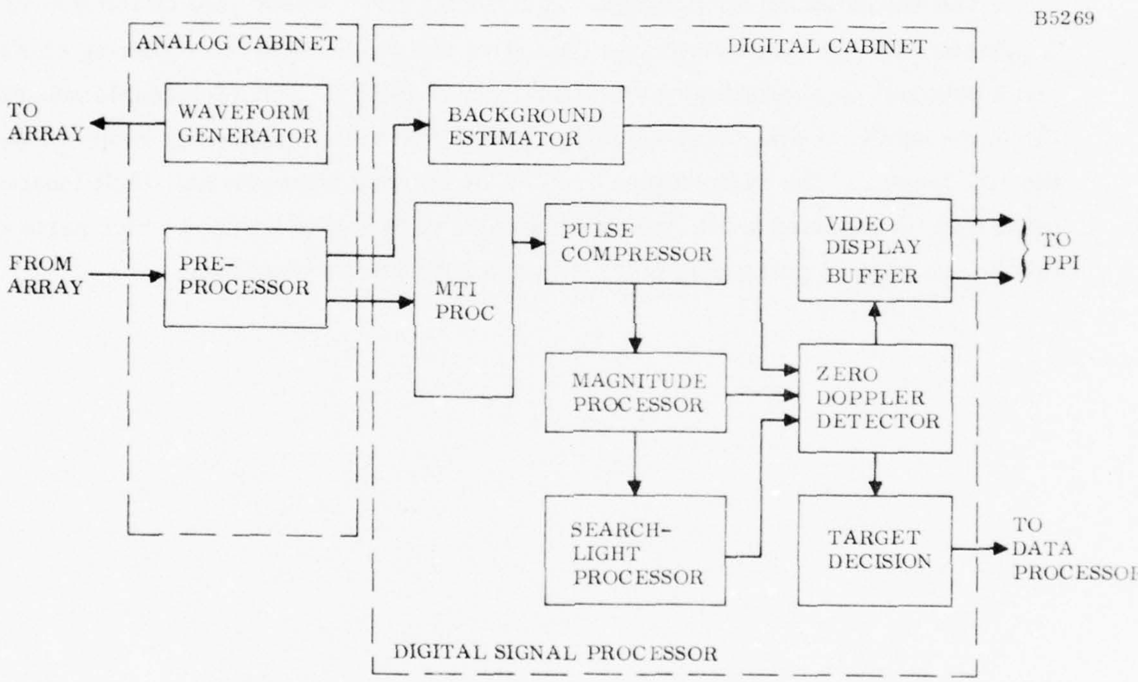


Figure 11-7. Signal Processing Subsystem Block Diagram

The waveform generator produces all LFM waveforms required for transmit and internal testing. The preprocessor accepts sum, azimuth-difference, elevation-difference, and sidelobe blanking signals at a 75-MHz IF from the antenna group. It operates on these signals to transform them into digital format. The functions it performs in the process include:

1. Automatic gain control (AGC)
2. Separating the pulses of the frequency diversity waveform
3. Amplitude weighting to achieve -30 dB range sidelobes after pulse compression
4. Synchronous detection to generate in-phase (I) and quadrature (Q) video modulation signals for each of the two sub-pulses on each of the four beams
5. A/D conversion of the video modulations

The digital signal processor performs the bulk of the processing for the radar. The block diagram, Figure 11-7, indicates the seven main functions. The digital MTI's cancel terrain and weather clutter on each of the 16 input channels (4 frequencies, 4 beams). They are "integrate-and-dump" type MTI's capable of integrating virtually any number of pulses, with any complex weight set, and with a wide range of permissible stagger codes. The MTI configuration is established in real time by a word output from the radar control computer.

A single pulse compression network processes all 16 signals. It compresses LFM signals with a BT product of 8 in the short-range interval or 32 in the long-range interval. The heart of the pulse compressor is the FFT-16. Coupled with an appropriate input distribution network and an output summing network, it can be used to match filter LFM signals with BT products of 8, 16, 32, 64, 128, or 256. It provides a pulse compression gain of 23.4 dB while maintaining range sidelobes of -30 dB.

The background estimator is used for background normalization, a Constant False Alarm Rate (CFAR) technique which is implemented as part of the target decision logic. Each sum-beam range cell is compared to a background-level estimate derived by averaging the sum beam output over a range interval equal to the uncompressed pulse duration. Sidelobe blanking is also employed as part of the target decision logic to ensure the detection of mainlobe signals only.

The video buffers perform the dual functions of aligning the asynchronous radar data with the periodic display sweeps and recirculating the video data for several cycles, depending on signal amplitude in order to produce an azimuth stretch to the single hit data derived by the 3-D radar. The resultant display video is a blip characteristic of 2-D systems with a conventional high hit-per-scan rate.

b. DATA PROCESSING SUBSYSTEM

(1) Summary Description

The data processing subsystem of the radar is responsible for all system control, function scheduling, postdetection processing, target tracking and target information reporting. Figure 11-8 identifies the major data processing subsystem components, and shows their relationship to the radar system. Primary control and data flow paths are also indicated. The radar will be controlled by a minicomputer.

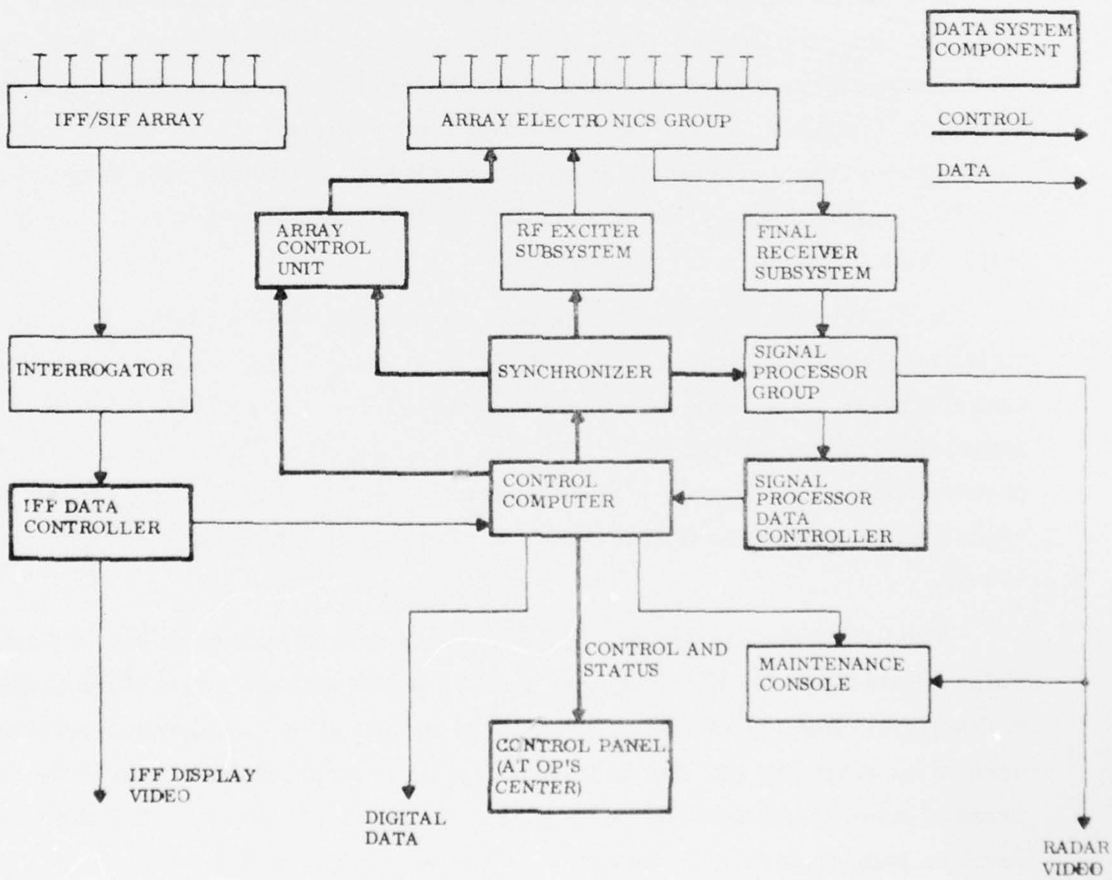


Figure 11-8. System Control and Data Flow

Each period of system operation is scheduled and configured by the control computer. For each period of operation the computer specifies detailed control information, including the waveform, signal processing parameters, frequency channel, detection thresholds, MTI weights, and range time. This information is passed to the synchronizer in the form of coded instructions which, when executed, cause the required timing signals and operations which operate the system to occur. Beam-steering phases and individual row control data are produced by the computer and sent directly to the array via the array control unit during current operating time. Information pertaining to each row is held in registers within the row electronics. When the next period of operation begins, a switching strobe, generated by the synchronizer, causes this data to be applied to phase shifters and control electronics within the rows.

All system functions which require system time, whether passive or active, are scheduled and controlled in this manner. In addition to programmed search operation, these functions consist of weather clutter tests, performance tests, calibration measurements, and ECCM functions. Control is exercised entirely through manipulation of subfields within the synchronizer and array control instructions. Thus, the system is dynamically adaptable to a changing clutter or ECM environment and, for the long term, is readily adaptable to a changing threat environment. This feature is clearly important for protecting the system against obsolescence, especially during the rapid technology growth envisioned within the next 20 years.

Data produced by the various system operations is put into a suitable message format by the signal processor data controller for transmission to the control computer. Included with this data is an identification field which tells the computer what system operation produced it. In this way, the processing and reporting of all radar information is decoupled from time-critical system operation. Data is put in a buffer and processed in accordance with a predetermined priority scheme.

An IFF data controller accepts the interrogator output and generates defruited digital target reports containing validated mode and code information for interlaced operation. Synchronous video outputs are also produced for local and remote display. The computer accepts the IFF target reports, which are asynchronous with the radar, and associates them with corresponding radar reports. In this way, combined IFF and radar target reports are produced for reporting on the data link.

Requests for system performance status and fault location data are received from the CRT terminal at the maintenance console. The requested data is then properly formatted and presented on the CRT display.

All of the data processor subsystem components monitor their own performance, as well as the performance of the radar system areas with which they interface. In this way, status of the entire radar system is made continuously available to the computer to be used for reporting and fault location.

(2) Computer Program Functional Description

System operation and postdetection processing functions are performed by a computer program composed of 15 major functional modules. These modules are data driven; they are scheduled by a supervisor program for execution when data is present at their inputs. Input data are presented to the modules in First-In-First-Out (FIFO) queues and the module outputs are placed in queues. Scheduling of computer resources thus takes place through a procedure of monitoring both these queues and the various Input/Output Controller (IOC) interrupts resulting from Input/Output (I/O) activity. Figure 11-9 is a diagram of the functional modules and the information flow among them.

System activities are scheduled by the radar function scheduler based on a prioritization of requests presented by three external request queues and a self-contained search queue. The schedule, consisting of a sequential set of items in a schedule queue, is serviced by the radar control program, which computes array phases and selects the required control instructions to present to the synchronizer. These instructions and control data are output to the synchronizer and array control unit, where they are held in memory until the moment of execution.

Detections or data generated by the radar system are presented by the signal processor data controller to the radar data input processor. This information is preceded, at the start of each period of system activity, by a header record which identifies the activity which produced the data which follows. In this way, the scheduling and execution of radar functions are decoupled in time from the processing of the resulting data. The radar data input processor uses the identification fields of the header record to sort the data into queues which drive the modules designed to process it.

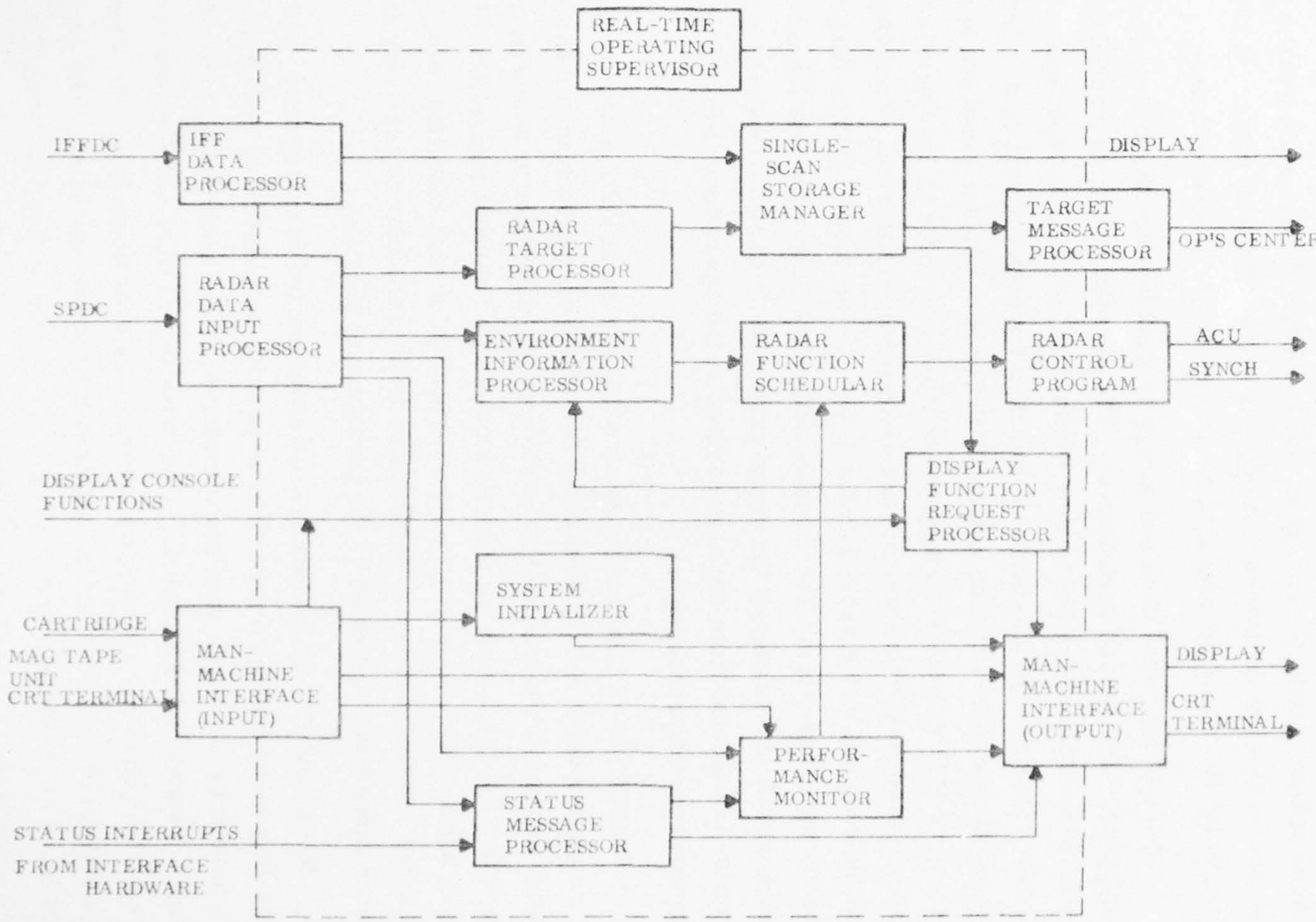


Figure 11-9. Computer Program Summary Functional Diagram

The first of these processing modules is the radar target processor which performs a postdetection processing function. Corrected values of azimuth and elevation are computed, height is calculated, and redundant detections in two dimensions are eliminated through an association process with single scan store. In addition, special processing functions are provided for processing ECCM detections.

Some of the radar time and energy is used to adapt the system to a changing clutter and interference environment. The associated data is steered to the environment information processor module which monitors the elevation and azimuth of clutter. Optimum MTI weights are selected for each azimuth sector and for two sectors in elevation to cancel clutter returns with variable Doppler mean and spread. Waveforms and MTI weights are staggered on alternate scans to eliminate blind speeds. Tables of these optimum weights are updated periodically and automatically by presenting requests to the radar function schedular for transmissions designed to measure clutter parameters. These tables are used by the schedular for control of short-range search processing by the signal processor. Operator override control over this process is executed from the control panel at the Operations Center via the display function request processor.

Other types of information obtained via the radar data input processor consist of status messages and data resulting from schedule performance monitoring tests. Status messages are produced by hardware-detected faults or specialized time-dependent information which must be input under interrupt control (for example, the array north reference mark). A certain portion of each elevation scan, approximately 6% under normal conditions, is allocated by the schedular to servicing calibration and performance tests requested by the performance monitor.

Radar and IFF operations are not synchronized in this system, and association must take place through a procedure of position correlation on each scan. This function is provided by the single scan store manager, which receives its inputs from separate queues of radar and IFF reports. The process will work using either remote or colocated IFF equipment, although the addition of a coordinate transformation to the IFF data processor module would be required for remote operation. The single-scan store manager also provides long-term position stationarity logic to detect the presence of clear air clutter. Targets which exhibit Doppler and pass through the postdetection processing logic, but that which do not change their average position over a number of scans, are maintained in store and reporting of them is inhibited.

Single-scan store also serves as a data base for interaction with the display and for reporting validated target data on each scan via the target message processor module. This module searches linearly through the store and formulates messages for reporting over the data link for targets that have been enabled for reporting by the single scan store manager.

c. MAINTENANCE CONSOLE

The maintenance console consists of a CRT terminal, a PPI display, and a special board tester. The CRT terminal includes an alphanumeric display and a keyboard with nine function keys and, as a minimum, the standard 64-character American Standard Code for Information Interchange (ASCII) set. The CRT terminal is the vehicle through which detailed performance and fault location status information is requested and presented. It is also used in system initialization to input parameters such as radar height, refractivity index, elevation coverage limits, allowed frequencies, and weather mode update interval.

The PPI display will provide to the maintenance men data and controls which closely mirror the data and controls displayed at the Operations Center consoles. The intent here is to provide a solid basis for evaluating the quality of the video and detected target data radar outputs.

SECTION XII

BUDGETARY 3-D RADAR PROCUREMENT SCHEDULE AND COSTS

1. DEVELOPMENT AND ACQUISITION

Cost estimates were prepared for the development, testing, and production of twenty 3-D minimally attended radars. A nominal schedule is shown in Figure 12-1. The Engineering Development phase provides all of the nonrecurring engineering and manufacturing effort to produce and test the first system and prepare for production of 19 more at the rate of one per month.

The budgetary costs associated with this schedule assume that the following items are to be government-furnished, and costs are therefore not included for them.

- Transportation
- Helicopter Services
- Tower, Radome, and Shelter
- Site Preparation
- Prime Power

Costs are likewise not included for technical orders, training and instruction books, and spares. All costs are in 1976 dollars.

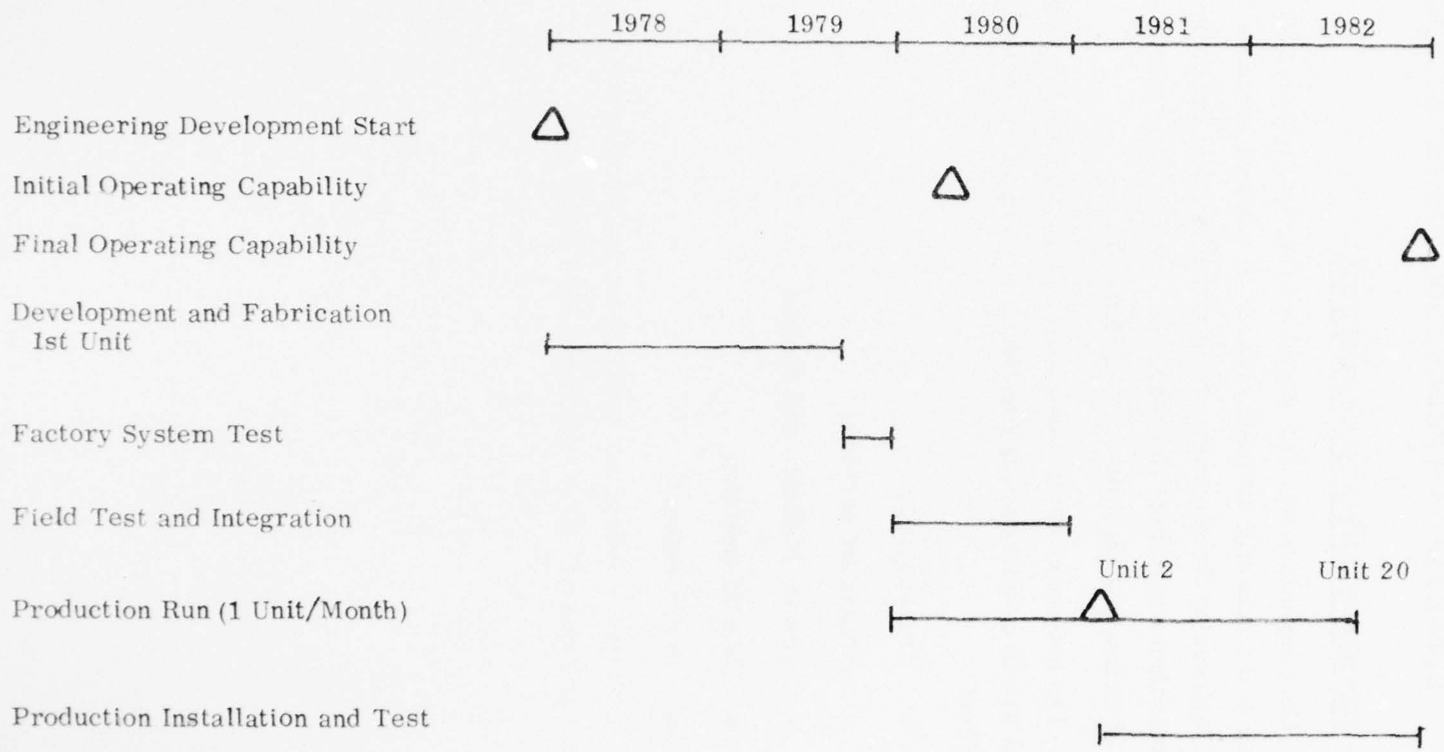


Figure 12-1. 3-D Development and Acquisition

2. OPERATIONS AND MAINTENANCE COSTS

Costing of the 3-D radar follows the same format as the 2-D radar costings.*

The following items are included as Operational and Maintenance (O&M) costs:

Initial and Replacement Spares
Material Cost of Repair
Labor Cost of Repair
Supply Item Management
Prime Power Costs
Test Equipment Cost
Personnel (on site)
Training

a. COST METHODOLOGY

The 3-D radar can be broken into 18 main cost categories. The same data is required for each category as for the 2-D radar. Table 12-1 lists these parameters.

The key assumptions made in this analysis are:

1. All costs based on 1976 dollars.
2. All spares are produced during initial system construction or no retooling is required to construct new spares.
3. Radar life is 20 years with no salvage value.
4. No on-site repair of failed components.

b. TEST EQUIPMENT COSTS

Test equipment costs are based on the requirement for two sets of test equipment. First, a complete set of equipment is needed at each depot. This set consists of:

1.	Standard Tools	$4,200
2.	Standard Test Equipment	200,000
3.	Special Test Equipment and Tools	61,000
		$265,200

* See Volume II, 2-D Unattended Radar.

TABLE 12-1. 3-D SYSTEM COMPONENT PARAMETERS

Category	Quantity QTY_i	No. of Types $NTYP_i$	(Failures Per 10^6 h) FR_i	% Condemn On Fail $COND_i$	On Site Labor Man-Hours BMH_i	Depot Labor Man-Hours DMH_i	Repair Parts Cost $ RPC_i
Large Digital Boards	220	100	6	1	0.33	0.33	50
Analog Boards	176	70	5	1	0.33	0.33	50
Power Supplied	22	18	10.0	1	0.33	1.0	50
RF Power	440	1	5.47	100	0.33	0	0
Integrated Receiver	44	1	20	1	0.33	0.33	50
Logic Pack	11	1	16.34	1	0.33	1.0	50
Row Power Supply	11	1	27	1	0.33	1.0	50
Circulator	44	1	0.05	100	0.33	0	0
Row Feed Boards	44	1	1.0	1	0.33	1.0	50
Drive Motor	1	1	20	1	0.33	1.0	50
Gear Box	1	1	1.0	1	0.33	1.0	50
Bearing	1	1	1.0	100	0.33	0	0
Slip Rings/Rotating Joint	1	1	10.0	1	0.33	1.0	50
Tilt/Temp Sensors	1	1	1.0	1	0.33	1.0	50
Encoder	1	1	10.0	1	0.33	1.0	50
Power Pack	44	1	15.95	1	0.33	1.0	370
Column Feed	2	1	2.43	1	0.33	1.0	5000
Equipment Plate	9	1	4.5	1	0.33	1.0	100

The second set is to be provided for each site, and will be assumed to consist of 1/3 of the standard test equipment and tools listed above.

Calibration, repair and replacement of test equipment is assumed to be 5% of the initial equipment cost per year.

Table 12-2 summarizes the per site and per depot test equipment costs. The costs for 20 years assuming 20 sites and two depots are also shown.

TABLE 12-2. TEST EQUIPMENT

Item	Per Site	Per Depot	20 Sites	2 Depots
Standard Tools	1,400	4,200	28,000	8,400
Standard Equipment	67,000	200,000	1,340,000	400,000
Special Tools and Equipment	-	61,000		122,000
Subtotal	68,400	265,200	1,368,000	530,400
Calibration and Repair (1 yr)	3,420	13,260	68,400	26,520
Calibration and Repair (20 yrs)	68,400	265,200	1,368,000	530,400
Total	136,800	530,400	2,736,000	1,060,800

c. PERSONNEL COSTS

The on-site personnel are listed below:

- 1 Operations and Maintenance technicians — Level E5
- 2 Operations and Maintenance technicians — Level E3
- 3 Overhead (cooks, watchmen, etc.) — Level E3
- 1 Site Commander — Level 03

Costs are generated only for the 20-year operation. Data required to compute the personnel costs are:

1. Salary (SAL)

SAL(E5)	\$10,550
SAL(E3)	7,275
SAL(03)	20,751

2. Off-base living support factor (LS)

   $LS = 1.186$

3. On-site O&M personnel operation factor (OPF). Basically, it takes nearly 5 men to keep 3 men on duty full time due to vacations, etc. Therefore,

   $OPF = 1.6$

Per year, per system on site personnel costs, P, are then given by:

$$P = (1.186)(1.6)(1\ SAL(E5) + 5 \cdot SAL(E3) + 1 \cdot SAL(03)) \tag{12-1}$$

which yields

$$P = \$128,442 \tag{12-2}$$

Total 20 systems, 20 year personnel costs, PT are:

$$PT = P \cdot 20 \cdot 20 = \$51.37M \tag{12-3}$$

d. PERSONNEL TRAINING COSTS

Training costs must include the cost of training instructors, cost of training O&M personnel, and the cost of material used in training. Training begins before the first radar is deployed and continues throughout the life of the radar (due to personnel turnover).

Based on an internal LCC study, training costs amount to approximately 15% of the total O&M personnel costs, under the following assumptions:

- 50% yearly turnover rate
- 11-12 average class size
- 4:1 student to teacher ratio
- 3-month course length 5 days/week, 8 hours/day

From Equation (12-3) then, the total 20 year-20 system training costs,

$$TC = (0.15)(51.37) = \$7.71M \tag{12-4}$$

e. LIFE CYCLE COSTS

The same equations may be used for costing the 3-D radar as were used for the 2-D radars. The differences are the components themselves (from Table 12-1) and the overall system parameters (which are listed in Table 12-3).

The 20 year-20 system cost breakdown (i.e., a subset of total Life Cycle Costs) is shown in Table 12-4, and per system-per year costs are shown in Table 12-5.

TABLE 12-3. SYSTEM PARAMETERS

Symbol	Description	Units	Value
NSYS	No. of systems		20
NYR	No. of years in the radar life	yr	20
YOH	Yearly operating hours	h	8760
$CPIM_R$	Cost to maintain an item in the government inventory	\$/item	105
$CPIM_I$	Cost to enter an item into the government inventory	\$/item	500
DRCT	Depot Repair Cycle Time (Fraction of the total radar life)		0.00833
BLR	Base labor rate	\$/mh	20
DLR	Depot labor rate	\$/mh	25
NI	No. of new items		1000
PT	Total power used	kW	42
CKW	Cost per kWh	\$/kWh	0.12
NSPARE	No. of spare storage sites*		20
NCAT	No. of component cost categories		15
NDEPOT	No. of depots		2

* This is a change from the 2-D Radar.

TABLE 12-4. TOTAL 20 YEAR-20 SYSTEM, 2 DEPOT O&M COSTS

Material Cost of Repair	$1.67M
Spares Cost	8.15
Base Labor Cost (Maintenance)	0.161
Depot Labor Cost (Maintenance)	0.218
Inventory Management	0.605
Power Cost	17.660
Test Equipment (Site)	2.736
Personnel	51.4
Training	7.71
Test Equipment Depot	1.061
Total	$91.37M

TABLE 12-5. PER YEAR-PER SYSTEM COSTS

Material Cost of Repair	$4.19K
Spares	20.36
Base Labor	0.40
Depot Labor	0.55
Power	44.2
Test Equipment (Repair/Calibration)	6.84
Personnel	128.1
Total	$204.94K

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